UNIVERSIDADE FEDERAL DO RIO GRANDE DO SUL
INSTITUTO DE CIÊNCIAS BÁSICAS DA SAÚDE
PROGRAMA DE PÓS-GRADUAÇÃO EM MICROBIOLOGIA AGRÍCOLA E DO AMBIENTE

BENI JEQUICENE MUSSENGUE CHAÚQUE

AVANÇOS NA GARANTIA DE ÁGUA SEGURA: EXPLORANDO MÉTODOS ALTERNATIVOS COM FOCO NA INATIVAÇÃO DE BACTÉRIAS, PROTOZOÁRIOS E DEGRADAÇÃO FOTOCATALÍTICA DE FÁRMACOS E AGROTÓXICOS POR MEIO DA RADIAÇÃO SOLAR

Orientadora: Profa. Dra. Marilise Brittes Rott
Co-orientador: Antônio Domingues Benetti

Porto Alegre

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Tese apresentada ao Programa de Pós-Graduação em Microbiologia Agrícola e do Ambiente do Instituto de Ciências Básicas da Saúde da Universidade Federal do Rio Grande do Sul como requisito parcial para a obtenção do título de Doutor em Microbiologia Agrícola e do Ambiente.

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AVANÇOS NA GARANTIA DE ÁGUA SEGURA: EXPLORANDO MÉTODOS ALTERNATIVOS COM FOCO NA INATIVAÇÃO DE MICRORGANISMOS E DEGRADAÇÃO FOTOCATALÍTICA DE FÁRMACOS E AGROTÓXICOS POR MEIO DA RADIAÇÃO SOLAR

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RESUMO

A qualidade microbiológica da água determina a epidemiologia de doenças de transmissão hídrica em assentamentos humanos quando ela é usada para fins recreativos e principalmente para fins potáveis. A presente tese descreve as atividades que visaram contribuir para uma melhor compreensão dos riscos microbiológicos da água, e dos métodos alternativos de baixo custo de tratamento de água no ponto-de-uso. Também visaram o estudo da desinfeção solar (SODIS) e descontaminação fotocatalítica da água. Diferentes revisões críticas e sistemáticas com ou sem meta-análise foram conduzidas. Além disso, foi realizada a avaliação do desempenho da SODIS convencional, bem como dos sistemas de SODIS, e descontaminação fotocatalítica da água. Os nossos achados e seus significados são: (I) A prevalência global de amebas de vida livre (AVL) em águas usadas para recreação (piscinas e água superficiais) é alta (44.34%) e preocupante. (II) O papel da interação das AVL e diferentes vírus de importância médica (incluindo Sars-Cov-2) na persistência ambiental e evolução destes patógenos nos corpos de água merece atenção dos pesquisadores. (III) Os sistemas de SODIS operando em fluxo contínuo ou intermitente de grande vazão podem ser usados no aprovisionamento público em larga escala de água potável segura a baixo custo. (IV) O sucesso no combate de doenças de transmissão hídrica pelo uso de tecnologias de baixo custo de tratamento domiciliar de água é influenciado por barreiras e facilitadores enquadrados no domínios psicossocial, promocional e tecnológico. O treinamento adequado dos usuários e a adoação das tecnologias, combinados com alta adesão, são importantes preditores de sucesso. (V) O uso consistente do SODIS resulta em ganhos epidemiológicos devido à melhoria na segurança microbiológica da água potável, e da indução de mudanças imunológicas protetivas (especialmente durante os surtos). (VI) A SODIS convencional (24 horas cumulativas) em condições de forte insolação natural é incapaz de inativar tantos os cistos de *Acanthamoeba castellanii* quanto *Pseudomonas aeruginosa* internalizadas, assim a água desinfetada precisa ser consumida dentro de três dias. (VII) O sistema de SODIS desenvolvido inativou cistos de *A. castelani* (10^3 cistos/L) e esporos de *Bacillus altitudinis* (10^2 UFC/mL), e tem potencial de ser utilizado no abastecimento de água potável em larga escala. (VIII) A integração de TiO_2 como fotocatalizador, ao sistema de SODIS permitou degradar simultaneamente doxiciclina (87%), sulfametoxazol (35,5%), dexametazona (32%) e carbendazim (31,8%) em apenas 15 minutos, o sistema tem potencial de ser aplicado em situação real de descontaminação química de água. (IX) Foi submetido um pedido de patente sobre o sistema no Instituto Nacional de Propriedade Industrial (INPI).

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ADVANCES IN GUARANTEING SAFE WATER: EXPLORING ALTERNATIVE METHODS FOCUSING ON THE INACTIVATION OF MICROORGANISMS AND THE PHOTOCATALYTIC DEGRADATION OF DRUGS AND PESTICIDES THROUGH SOLAR RADIATION

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ABSTRACT

The microbiological quality of water determines the epidemiology of waterborne diseases in human settlements when it is used for recreational purposes and mainly for human consumption. This thesis describes the activities that aimed to contribute to a better understanding of the microbiological risks of water and low-cost alternative methods for its treatment at the point of use. Also aimed to study solar disinfection (SODIS) and photocatalytic decontamination of water. Different critical and systematic reviews were carried out with or without meta-analysis. Furthermore, an evaluation of the performance of conventional SODIS as well as SODIS systems and photocatalytic water decontamination was carried out. Our findings and their significance are: (I) The global prevalence of free-living amoebas (FLA) in recreational waters (swimming pools and surface waters) is high (44.34%) and therefore worrying due to the microbiological risks. (II) The role of the interaction of ALF and different viruses of medical importance (including Sars-Cov-2) in the environmental persistence and evolution of these pathogens in water bodies deserves attention from researchers. (III) SODIS systems operating at continuous or intermittent high flow can be used for large-scale public supply of safe drinking water at low cost. (IV) Success in combating waterborne diseases through the use of low-cost household water treatment technologies is influenced by barriers and enablers belonging to the psychosocial, promotional and technological domains. Proper user training and adoption of proper technology, combined with high adherence, are important predictors of success. (v) Consistent use of SODIS results in epidemiological gains, which result from improved microbiological safety of drinking water and the induction of protective immunological changes (especially during outbreaks) in SODIS users. (VI) Conventional SODIS (24-hour cumulative exposure) under strong sunligth fails to deactivate Acanthamoeba castellanii cysts and internalized Pseudomonas aeruginosa. Therefore, the treated water must be consumed within three days. (VII) The developed SODIS system successfully inactivated *A. castelani* cysts (10^3 cysts/L) and *Bacillus altitudinis* spores (10^2 CFU/mL), and has the potential to be used in large-scale public drinking water supply. (VIII) The integration of TiO2 as a photocatalyst in the SODIS system allowed the simultaneous degradation of doxycycline (87%), sulfamethoxazole (35.5%), dxamethasone (32%) and carbendazim (31.8%) in just 15 minutes, the system has potential to be applied in a real situation of chemical water decontamination. (IX) A patent application for the system was filed with the National Institute of Industrial Property (INPI).

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LISTA DE ABREVIATURAS E SIGLAS

AIDS	Acquired Immunodeficiency Syndrome
AK	*Acanthamoeba* keratitis
ARM	Amoeba-Resistant Microorganisms
AVL	Amebas de Vida Livre
BSF	BioSand Filter
CFSSWD	Continuous Flow Systems for Solar Water Disinfection
CPC	Compound Parabolic Concentrator
CPTEC	Centro de Previsão do Tempo e Estudos Climáticos
CWF	Ceramic Water Filter
DPD	N,N-diethyl-p-phenylenediamine
EAG	Encefalite Amebiana Granulomatosa
FLA	Free-living amoebae
GAE	Granulomatous Amebic Encephalitis
HDWT	Household Drinking Water Treatment Technologies
INMET	Instituto Nacional de Meteorologia
INPE	Instituto Nacional de Pesquisas Espaciais
IR	Infrared
L	Litro
MAP	Meningoencefalite Amebiana Primária
mg	Miligramas
mL	Milliliter
MPN	Most Probable Number
NGO	Non-Governmental Organization
NMFC	Nanomateriais Fotocatalíticos
NMFR	Nanomateriais Foto-Reativos
NMFT	Nanomateriais Fototérmicos
NNA	Non-Nutrient Agar
NTU	Nephelometric Turbidity Units
ODS	Objetivos de Desenvolvimento Sustentável
OMS	Organização Mundial de Saúde
ONU	Organização das Nações Unidas
PAM	Primary Amoebic Meningoencephalitis
PCA	Plate Count Ágar
PcNM	Photocatalytic Nanomaterials
PCR	Polymerase chain reaction
PET	Polyethylene terephthalate
PoC	Ponto de Coleta
POU	Ponto de Uso
PTC	Parabolic Trough Concentrator
PtNM	Photothermal Nanomaterials
RSV	Respiratory Syncytial Virus
Sars-Cov-2	Severe acute respiratory syndrome coronavirus 2
SODIS	Desinfecção Solar – do inglês *Solar Disinfection*
SOPAS	Solar Pasteurization
UV	Ultravioleta
UNT	Unidade Nefelométrica de Turvação

1. INTRODUÇÃO

O acesso à água segura para consumo humano é um dos mais fundamentais requisitos para à vida, e um dos direitos humanos mais básicos. No entanto, o acesso á água em assentamentos humanos continua desigual no mundo, e prevê-se que se torne cada vez mais problemático com o passar do tempo (OMS 2019). O uso de água captada de fontes inseguras por cerca de 2 bilhões de pessoas continua causando mais de 800.000 mortes anuais no mundo por doenças gastrointestinais e parasitarias de transmissão hídrica, associadas à ingestão direta de água contaminada (OMS 2019; Prüss-Ustün et al., 2019). A desnutrição associada às perturbações gástricas relacionadas à ingestão de água insegura, as doenças associadas ao consumo de alimentos preparados com água contaminada, bem como as doenças relacionadas a práticas recreativas em corpos de águas biologicamente inseguras, contribuem com outra parcela de mortes.

Embora o consumo de água biologicamente insegura também ocorra em países desenvolvidos, as taxas de consumo e a mortalidade resultante de doenças de transmissão hídrica são incomparavelmente maiores nos países em desenvolvimento, especialmente em países pobres da África (53%) e Sudeste da Ásia (38%) (Bain et al., 2014). Os contextos destes países, muitas vezes caracterizados por uma multiplicidade de desafios, incluindo a falta de infraestrutura, baixo poder de compra, intenso êxodo rural, urgências de investimentos na saúde, educação, transporte, segurança e saneamento, faz com que o investimento em sistemas convencionais de água potável seja difícil, e relativamente menos prioritário. Estas e outras razões (incluindo, o fato da grande parcela das populações nestes países residirem em assentamentos rurais relativamente menos povoados), fazem com que o desenvolvimento e promoção de tecnologias não convencionais de aprovisionamento de água potável segura sejam valiosos e necessários (Chu et al., 2019).

As tecnologias de tratamento de água no ponto de uso (POU), dentre as quais se menciona a desinfecção solar (SODIS – do inglês *solar disinfection*), se destacam entre as tecnologias não convencionais que são adequadas para prover água potável segura e remediar as altas taxas de mortalidade por doenças de transmissão hídrica. Por este motivo o presente trabalho visou compreender e desenvolver os métodos alternativos de aprovisionamento de água segura para as diferentes necessidades humanas, dando-se um enfoque para a tecnologia SODIS, tanto de baixa bem como a de alta produtividade.

2. OBJETIVOS

2.1 Objetivo Geral

Investigar e promover avanços na garantia de água segura, mediante a exploração de métodos alternativos que se concentrem na inativação de bactérias, protozoários e na degradação fotocatalítica de fármacos e agrotóxicos, utilizando a radiação solar como recurso primordial.

2.2 Objetivos Específicos

2.2.1 Determinar a prevalência de amebas de vida livre nos corpos de água usados para recreação, por meio de revisão sistemática com meta-análise de estudos publicados até 2022.

2.2.2 Discutir as possibilidades e consequências da interação entre amebas de vida livre e vírus patogênicos incluindo Sars-Cov-2, com base na mais recente literatura.

2.2.3 Realizar revisão crítica sobre a necessidade, os avanços necessários, e desafios por superar para utilizar as tecnologias de desinfeção solar como alternativa para o abastecimento público de água potável em larga escala.

2.2.4 Revisar sistematicamente a literatura científica e patentearia sobre o estado da arte, e possibilidades para o futuro no desenvolvimento de sistemas de desinfeção solar de água aplicáveis no abastecimento em larga escala.

2.2.5 Conduzir uma revisão sistemática e crítica sobre os ganhos epidemiológicos e imunológicos resultantes da utilização da desinfeção solar.

2.2.6 Efetuar uma revisão sistemática para identificar e compreender os fatores que determinam o sucesso ou o insucesso do uso das tecnologias de baixo custo de tratamento de água potável no ponto de uso na prevenção das doenças de transmissão hídrica.

2.2.7 Avaliar a eficácia da desinfecção solar sobre cistos de *Acanthamoeba castellanii* e sobre *Pseudomonas aeruginosa* abrigadas no seu interior.

2.2.8 Aprimorar um sistema de desinfecção solar de água em fluxo contínuo autônomo, e testar sua eficácia para inativar microrganismos e para degradar fármacos e agrotóxicos.

3. REVISÃO DA LITERATURA

3.1 Acesso a água potável no mundo

Apesar dos aumentos consideráveis nas taxas de acesso a fontes melhoradas de água potável ao longo do século passado, as desigualdades no acesso à água potável continuam altas em todo o mundo. Cerca de 2 bilhões de pessoas não tem acesso a fontes melhoradas de água potável[1] (ONU, 2022, Figura 1). Estas pessoas consomem água captada de fontes contaminadas por fezes, e como consequência, 829.000 vidas são perdidas anualmente devido a doenças transmitidas pela água (Prüss-Ustün et al., 2019; Bain et al., 2021). Estima-se que as fontes de água potável são mais frequentemente contaminadas nas áreas rurais (41%, intervalo de confiança - IC: 31%-51%) do que nas áreas urbanas (12%, IC: 8-18%). A contaminação é mais prevalente na África (53%, IC: 42%-63%) e Sudeste Asiático (35%, IC: 24%-45%) (Bain et al., 2014).

Figura 1: Situação de acesso à água potável e suas implicações no mundo. Baseado nos dados da OMS, 2019.

Foi observado que a contaminação da água por *Escherichia coli* é substancialmente maior tanto no ponto de coleta (PoC) quanto no POU (intervalos 16-90% e 19-99% respetivamente). No entanto, a maior prevalência de *E. coli* na água foi positivamente associada às fontes não melhoradas,

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[1] Fontes de água potável melhoradas são aquelas que têm o potencial de fornecer água segura pela natureza de seu projeto e construção e incluem: água encanada, furos ou poços tubulares, poços escavados protegidos, nascentes protegidas, água da chuva e água envasada ou fornecida (OMS 2019).

famílias mais pobres, assentamentos rurais, presença de gado nos assentamentos e estaçõeso chuvosas (Bain et al., 2021; Chaúque et al., 2021).

Garantir o acesso universal e equitativo à água limpa para todos até 2030 é um dos ambiciosos objetivos dos Objetivos de Desenvolvimento Sustentável - ODS (ONU 2022). O alcance dessa meta é desafiado pelo alto investimento financeiro (US$ 37,6 bilhões) que precisa ser feito anualmente no mundo (por pelo menos 15 anos) para estender os serviços de água potável à populações sem acesso a fontes melhoradas (Guy & Mili 2016). Importa indicar que foi estimado que para o alcance desta meta, a velocidade atual de crescimento na expansão do acesso às fontes de água gerenciadas com segurança precisará ser quadruplicada (ONU, 2022). Estima-se que na velocidade atual de progresso do acesso a água potável, levando em consideração as estimativas de crescimento demográfico e os efeitos das mudanças climáticas até 2030, cerca de 1,6 e 2,8 bilhões de pessoas não terão acesso, respectivamente,à água potável e ao saneamento (ONU, 2022, Figura 2).

Figura 2: Situação de acesso água potável e saneamento seguros em 2030, se forem mantidas as taxas atuais de progresso na ampliação do acesso à água e saneamento. Baseado nos dados da OMS, 2022.

3.2 Risco protozoológico para saúde humana em águas recreativas

Embora com magnitude de importância epidemiológica relativamente menor, a qualidade microbiológica inadequada da água usada para fins de recreação representa um risco para a saúde humana. O risco está associado à ingestão involuntária (boca, nariz) da água contendo patógenos, ou ao contato com a superfície corpórea com os patógenos presentes na água (Graciaa et al., 2018). Além disso, a toxicidade da água relacionada à alta densidade de cianobactérias tóxicas é um indicador relevante de risco microbiano para saúde (Menezes et al., 2017).

Vários grupos de protozoários estão listados entre os mais importantes microrganismos de interesse médico associados às águas recreativas (Dorevitch et al., 2015).

As doenças humanas diretamente relacionadas aos protozoários nestes ambientes incluem doenças gastrointestinais, com destaque para as causadas por *Giardia* e *Cryptosporidium* (Dorevitch et al., 2015). A ceratite amebiana e encefalite amebiana granulomatosa (EAG) são causadas por *Acanthamoeba* (Visvesvara et al., 2007; Dos Santos et al., 2018; Sarink et al., 2022). A meningoencefalite amebiana primária (MAP) é causada por *Naegleria fowleri*, e raramente, por *Balamuthia mandrillaris* e *Sappinia pedatta* (Gelman et al., 2001; Visvesvara et al., 2007; Cope et al., 2019). Algumas destas doenças incluindo a MAP foram registradas em animais selvagens e domésticos (Leal Dos Santos et al., 2022; Ithoi et al., 2013; Karakus et al., 2016, 2017).

Os protozoários (com efase para as amebas de vida livre - AVL) representam um risco para saúde dos usuários de águas recreativas, inclusive para àquelas tratadas com desinfetantes, já que eles são resistentes aos diferentes processos bem estabelecidos de tratamento da água usada para esse fim (principalmente na forma de oo/cistos), incluindo o cloro e radiação ultravioleta - UV (Aksozek et al., 2002; Chaúque & Rott, 2021). Embora a UV seja considerada eficaz contra varios protozoários incluindo *Crytosporidium* e *Giardia*, não o é contra AVL (principalmente na forma de cistos). Além disso, as AVL têm sido associadas à persistência de patógenos bacterianos assim como virais (potencialmente Sars-Cov) na água, inclusive na água tratada com cloro (Thomas et al. 2004) ou com radiação UV (Boratto et al., 2014; Cervero-Aragó et al., 2014) o que as torna alvos interessantes de pesquisas sobre a eficiência de tecnologias de desinfeção de água.

A prevalência dos protozoários em diferentes corpos de água usadas para recreação estão documentados na literatura, para AVL (Saberi et al., 2020; Chaúque et al., 2022b), *Cryptosporidium* (Loganthan el at., 2012) e *Giardia* (Craun et al., 2005).

3.3 Tecnologias de baixo custo para desinfeção de água potável no ponto de uso

As tecnologias de baixo custo de tratamento domiciliar de água potável são reconhecidas como uma das ferramentas de curto e médio prazo mais adequadas para enfrentar a alta mortalidade por doenças associadas ao consumo de água não segura (OMS, 2019). Essas tecnologias são particularmente valiosas em assentamentos de países em desenvolvimento sem acesso a uma rede de distribuição de água potável tratada, onde a implementação de sistemas centralizados para o fornecimento de água potável tratada é um desafio ou um sonho distante (Fiebelkorn et al., 2012). Nestes países, os rios, lagos e poços rasos, geralmente altamente contaminados, são tidos como as principais fontes de água (Okpasuo et al., 2020; Chaúque et al., 2021; Bain et al., 2021).

Figura 3: Eficácia e custo de alguns métodos de tratamento domiciliar de água potável. Adaptado de García-Gil et al. (2021) com permissão https://creativecommons.org/licenses/by/4.0/.

A cloração, floculante-desinfetante, filtros lentos de areia, filtro de cerâmica, filtração por membranas operadas por gravidade, e SODIS estão listados entre tecnologias de baixo custo de tratamento de água no POU que se destacam por serem eficazes, acessíveis, populares, e aplicados a com sucesso em intervenções para melhorar a segurança de água potável (OMS, 2019; Chan et al., 2021). O uso das tecnologias de baixo custo de tratamento de água no POU foi consistentemente atribuído à redução do risco de diarreias e cólera (≥ 50%) em nível comunitário (Luby et al., 2006; Wolf et al., 2022).

3.3.1 Cloração domiciliar

É um método de tratamento químico de água potável bem estabelecido e de uso histórico. Consiste em adicionar compostos de cloro (por exemplo, hipoclorito de sódio, pastilhas de cloro) na água de modo a estabelecer uma concentração de cloro livre residual entre 0,2 a 0,5 mg/L (Nielsen et al., 2022). Nessas concentrações, o cloro é capaz de eliminar a maioria dos microrganismos patogênicos conhecidos (com algumas exceções, oocistos de Cryptosporidium, cistos de *Giardia* e *Acanthamoeba* (Zhou et al., 2014; Chaúque & Rott 2021)) dentro de 30 - 60 minutos de tempo de contato, bem como impedir seu novo crescimento na água (Meierhofer et al., 2019). Existe uma preocupação com a saúde devido à possibilidade de formação de uma grande variedade de subprodutos de desinfecção na água pelo uso de cloro (OMS, 2017), no entanto, estudos de campo apontam que a concentração desses subprodutos não excedem as diretrizes da OMS (Lantagne et al, 2010). A cloração doméstica de água potável, em escala comunitária resultou em redução (35-71%) no risco de diarreias (Arnold & Colford 2007; Solomon et al., 2021).

Tabela 1: Caracterização de desinfetantes à base de cloro como tecnologia de tratamento domiciliar de água potável (OMS, 2019).

Desempenho microbiano	- Eficaz contra vírus e bactérias. - Ineficaz contra cistos de protozoários, como *Cryptosporidium*.
Principais fatores que afetam a eficácia	- Conteúdo orgânico e turbidez. - Concentração de cloro livre. - Tempo de contato.
Vantagens	- Proteção residual contra recontaminação. - Simples de usar. - A produção local pode beneficiar a economia. - Baixo custo. - Portátil; peso leve, facilmente embalado e fácil de transportar em emergências.
Limitações	- Menos eficaz em águas turvas ou ricas em orgânicos e inorgânicos. - Os usuários podem se opor ao gosto e odor. - Necessidade de ajustar a dosagem para atender à demanda variável de cloro na água. - Necessidade de garantir o controle de qualidade do cloro fabricado localmente.
Aplicação	Mais apropriado quando: - o patógeno em questão é conhecido (por exemplo, *Vibrio cholerae*), pois o cloro não fornece proteção contra alguns protozoários. - a água apresenta baixo conteúdo orgânico e turbidez.

3.3.2 Floculante-desinfetante

Este método utiliza o efeito sinérgico do floculante e do cloro. O seu desenvolvimento resultou da necessidade de superar a baixa eficácia da cloração em condições de alta turbidez da água bruta (Crump et al., 2004). Normalmente o produto é comercializado na forma de um pó ou pastilha, que ao ser adicionado à água, desencadeia a precipitação, coagulação e floculação do material particulado suspenso na água (metais, matéria orgânica, microrganismos), ao mesmo tempo em que libera cloro livre residual. A água tratada se torna visualmente límpida, e química, física e biologicamente segura para beber (Souter et al., 2003).

As promoções do uso doméstico de um floculante-desinfetante a nível comunitário por intervenções que visavam melhorar a segurança da água potável resultaram na redução da prevalência e do risco de diarreia entre 25 – 64% (Luby et al., 2006; Crump et al., 2005; Rogers et al., 2019).

Tabela 2: Caracterização do uso de floculante-desinfetantes no tratamento domiciliar de água potável (OMS, 2019).

Desempenho microbiano	Eficaz contra bactérias, vírus e protozoários.
Principais fatores que afetam a eficácia	• Material floculante/desinfetante. • Tempo de contato. • Condições de mistura.
Vantagens	• Proteção residual contra recontaminação. • Melhoria visual na água tratada. • Redução de alguns metais pesados (por exemplo, arsénio) e pesticidas associados a partículas. • Portátil; leve, fácil de embalar e fácil de transportar em caso de emergência.
Limitações	• Múltiplas etapas necessárias para usar o produto. • Alto custo relativo por litro de água tratada. • Possíveis objeções de sabor e odor do usuário.
Aplicação	Mais apropriado quando: • a água é de turbidez relativamente alta.

3.3.3 Filtros lentos de areia (filtro BioSand)

É uma tecnologia de purificação de água que combina processos biológicos e físico-químicos que ocorrem no meio filtrante de areia para remover contaminantes (Freitas et al., 2022). O filtro lento de bioareia é essencialmente constituído por uma coluna composta por sucessivas camadas de areia e cascalho de diferentes granulometrias, contendo biofilme microbiano estabelecido na superfície de sua camada superior (Freitas et al., 2022). Além de ser eficaz na remoção de microrganismos patogênicos, turbidez e alguns contaminantes químicos da água (Romero et al., 2020; Lubarsky et al., 2022), a promoção do uso doméstico de BSF tem sido implicado na redução significativa do risco de diarreia (Moropeng et al., 2018).

Tabela 3: Sumarização do desempenho microbiano, limitações e vantagens dos filtros lentos de areia.

Desempenho microbiano	- Eficácia moderada a alta contra bactérias e protozoários. - Eficácia limitada contra vírus.
Principais fatores que afetam a eficácia	- Características do meio filtrante (tamanho efetivo e coeficiente de desuniformidade) - Qualidade da camada de biofilme formado no topo da camada filtrante. - Taxa de filtração.
Vantagens	- Melhoria da qualidade física, química e microbiológica da água. - Melhoria do sabor da água. - Simples de usar. - Nenhuma fonte de energia é necessária. - A possibilidade de produção local pode beneficiar a economia e facilitar o abastecimento. - Baixo custo relativo por litro de água tratada.
Limitações	- Variabilidade na qualidade dos filtros produzidos localmente. - Frágil; difícil de transportar em longas distâncias. - Filtros e receptáculos precisam ser limpos regularmente. - Eficacia reduzida nos primeiros dias (até a maturação do filtro), e após a manutenção do filtro. - Mau uso do filtro pode levar resultar em desagradável da água. - A taxa de fluxo é baixa em 1–3 L/hora (mais lenta em águas turvas).
Aplicação	Mais apropriado quando: - água bruta apresenta baixa turbidez (até 10 UNT). - há capacidade e produção de filtro de qualidade comprovada.

3.3.4 Filtros de cerâmica

É uma tecnologia de baixo custo para tratamento de água potável que, utiliza processos físicos e químicos (exclusão de tamanho e adsorção) para remover diversos contaminantes da água, principalmente microrganismos. Comumente é feito de uma estrutura de terracota contendo uma região filtrante microporosa, podendo ou não ser impregnada com agentes bacteriostáticos, como coloidais ou nanopartículas de prata ou cobre (Akowanou & Aina 2021). Filtros de cerâmica são comumente disponíveis como potes e velas, embora discos também estejam disponíveis (Clasen & Boisson 2006). O tamanho dos poros e a qualidade da fabricação são os principais determinantes do desempenho dos filtros cerâmicos; eles normalmente não são eficazes contra microrganismos menores, como vírus.

Os filtros foram amplamente demonstrados como eficazes (Morris et al., 2018), sustentáveis (Ren et al., 2013) e socialmente aceitáveis (Akowanou & Aina, 2021), capazes de reduzir significativamente o risco de diarreia quando promovido como uma tecnologia doméstica de tratamento de água potável (Clasen et al., 2004; du Preez et al., 2008).

Tabela 4: Sumarização do desempenho microbiano, limitações e vantagens dos filtros de cerâmica (OMS, 2019).

Desempenho microbiano	- Eficaz contra a maioria das bactérias e protozoários. - Eficácia limitada contra vírus.
Principais fatores que afetam a eficácia	- Meio filtrante e tamanho dos poros. - Qualidade de fabricação. - Quociente de vazão da água.
Vantagens	- Probabilidade mínima de re-contaminação quando mantido em recipiente de armazenamento seguro integrado. - A aparência da água tratada é melhorada, fornecendo um indicador visual que reforça os benefícios do tratamento. - Alteração mínima no sabor da água. - Simples de usar. - Nenhuma fonte de energia é necessária. - A possibilidade de produção local pode beneficiar a economia e facilitar o abastecimento. - Baixo custo relativo por litro de água tratada.
Limitações	- Variabilidade na qualidade dos filtros produzidos localmente. - Frágil; difícil de transportar em longas distâncias. - Filtros e receptáculos precisam ser limpos regularmente. - A taxa de fluxo é baixa em 1–3 L/hora (mais lenta em águas turvas).
Aplicação	Mais apropriado quando: - o patógeno em questão é conhecido (por exemplo, Cryptosporidium), pois a filtração de cerâmica não fornece proteção contra vírus entéricos. - há capacidade e produção de filtro cerâmico de qualidade comprovada.

3.3.5 Filtração por membrana acionada por gravidade

A filtração por membrana acionada por gravidade (FMAG) é uma técnica de baixo custo de tratamento microbiológico e físico da água a nível domiciliar ou comunitário desenvolvido na ultima década. A FMAG consiste de membranas através das quais a água passa em baixas pressões obtidas por meio da força gravitacional. Um biofilme é formado na membrana e ocorre uma estabilização do fluxo (em ~5 dias) que é relacionado a processos biológicos dentro da camada de biofilme na membrana. Isso permite uma operação estável durante um ano ou mais sem qualquer limpeza ou descarga. Dependendo da composição da água bruta de alimentação, o fluxo se estabiliza em um valor de 4–10 Lm^{-2}/h (Pronk et al., 2019). O uso de um sistema de FMAG em escala comunitário que que removia até 2 log de bactérias indicadoras de contaminação fecal na água tratada, resultou na diminuição de 31,5% na prevalência de diarreias na Indonésia (Sudiyani et al., 2022).

3.3.6 Desinfeção solar de água – SODIS

A SODIS é um método que se vale das propriedades biocidas da radiação UV e calor do sol para inativar microrganismos presentes na água. Ela foi documentada pela primeira vez em 1980, ao expor soro de reidratação horas em bolsas plásticas diretamente ao sol, os pesquisadores atribuíram o efeito biocida a faixa ultravioleta da radiação solar (Acra et al., 1980). A irradiação UV (UVA - 320-400 nm and UVB - 280-320 nm) danifica os ácidos nucléicos, prejudicando assim sua capacidade de replicação. Enquanto isso, moléculas fotossensíveis na água absorvem a luz visível, resultando em atividades oxidativas que danificam as estruturas celulares. A exposição à luz solar também resulta em aumentos de temperatura que desnaturam proteínas dentro dos microrganismos e/ou causam danos oxidativos associados a produtos de oxigênio dissolvido e calor (Nelson et al., 2018).

A técnica SODIS convencional consiste em colocar água não tratada em recipientes (~ 1,5 – 25 l) que transmitem radiação UV e expô-los ao sol por pelo menos 6 horas em dias ensolarados, ou por até 12 horas para dias com nebulosidade de > 50% (García-Gil et al., 2021).

A eficácia da SODIS como método de aprovisionamento de água potável segura foi amplamente demonstrada contra os representantes de todos os grupos de microrganismos incluindo vírus, bactérias, fungos e protozoários (Chaúque & Rott, 2021a; Hong et al., 2022). A promoção e o uso da SODIS pelas comunidades foram amplamente atribuídos à redução de 20-75% no risco de diarreia, e as taxas de redução são proporcionalmente maiores quanto maior a regularidade do uso (Rai et al., 2010; Soboksa et al., 2020).

Tabela 5: Visão geral do desempenho microbiano, limitações e vantagens das tecnologias de desinfeção solar (OMS, 2019).

Desempenho microbiano	- Eficaz contra vírus, bactérias e protozoários.
Principais fatores que afetam a eficácia	- Condições climáticas. - Tipo de material do recipiente. - Matriz de qualidade da água, incluindo turbidez.
Vantagens	- Probabilidade mínima de recontaminação quando mantido em recipiente desinfetante. - Simples de usar. - Baixo custo relativo por litro de água tratada. - Pouca ou nenhuma manutenção. - Mudança mínima no sabor da água.
Limitações	- Necessidade de pré-tratamento de águas de alta turbidez (por exemplo, > 30 NTU) por filtração ou floculação - Volume a tratar dependente da disponibilidade de recipientes limpos e intactos. - O tempo necessário para tratar a água é relativamente longo e varia de acordo com a intensidade do sol (aproximadamente 6 h sob 50% de céu nublado) - Os contêineres devem ser colocados onde serão expostos à luz solar e não perturbados (por exemplo, em um telhado) - Pode não ter um indicador visual para indicar o tratamento completo
Aplicação	Mais apropriado quando: - a água é de baixa turbidez. - recipientes limpos, transparentes e intactos para tratamento estão disponíveis.

3.3.6.1 Impactos epidemiológicos e imunológicos do uso da SODIS

As evidências atualmente disponíveis na literatura sugerem de forma consistente que a redução do risco de doenças gastrointestinais advindos do uso da SODIS resultam da combinação do efeito do consumo de água potável biologicamente segura e da ingestão de microrganismos não viáveis com importantes propriedades imunogênicas. Relatos de episódios reduzidos de diarreia e episódios de diarreia grave, entre usuários de SODIS (Conroy et al., 1996, 1999), mesmo em uma situação em que 86% das crianças também bebiam água não tratada (Rose et al., 2006), ou durante o surto de cólera (Graf et al., 2010), corroboram estudos que sugerem um efeito imunológico protetor em usuários de SODIS (Ssemakalu et al., 2014; 2021; Chaúque et al., 2022; Figura 4).

A efetiva indução de mudanças imunológicas que resultem em efeitos protetivos mediante a ingestão de patógenos inativados pela SODIS está relacionada ao mecanismo de inativação microbiana pelo sol, que causam danos celulares, porém, sem comprometer grande parte das propriedades imunogênicas dos microrganismos (Ssemakalu et al., 2015, 2020, 2021).

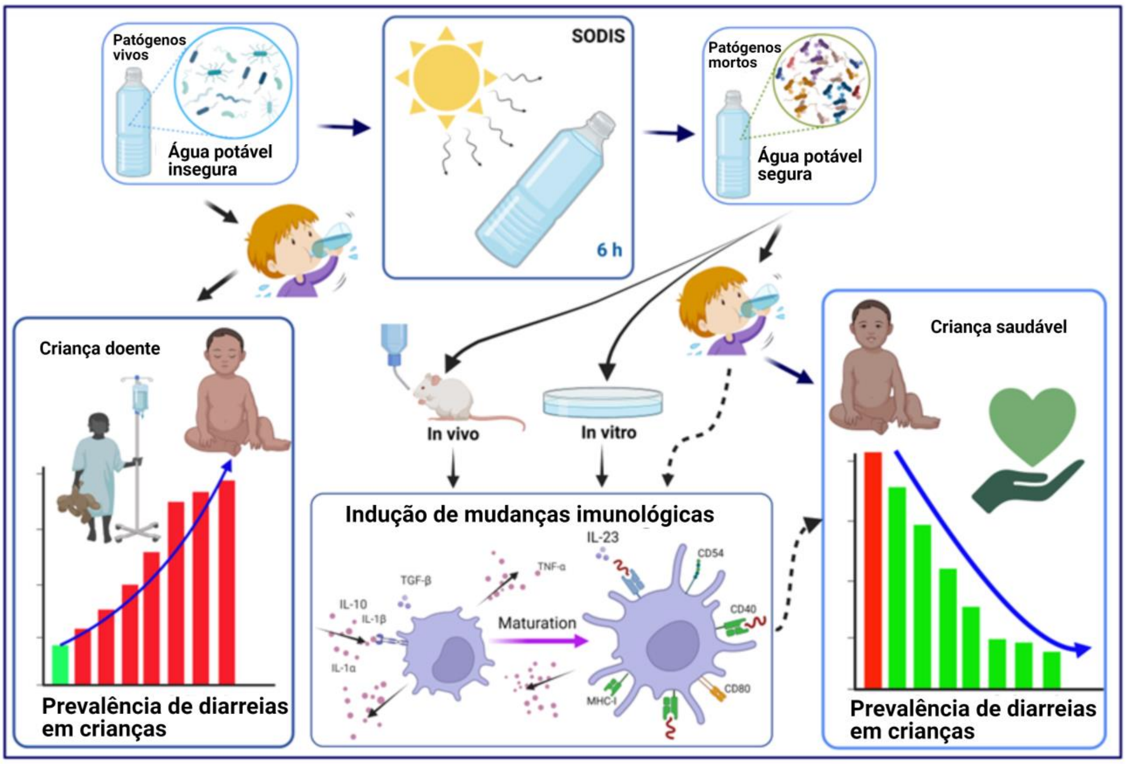


Figura 4: Visão geral da indução de mudanças imunológicas protetivas por microrganismos inativados através da desinfeção solar (Chaúque et al., 2022).

É importante notar que embora o risco reduzido de diarréia persista em todas as circunstâncias entre os usuários de SODIS, a indução de mudanças imunológicas que resultam em benefícios protetores ocorre quando a água bruta é contaminada com pelo menos uma densidade igual ou maior que a dose infecciosa do patógeno correspondente (Ssemakalu et al., 2014, 2021; Chaúque et al., 2022). Assim se entende que, há uma chance maior de que o uso do SODIS resulte em ganhos imunológicos durante surtos (Ssemakalu et al., 2021; Chaúque et al., 2022). Esses efeitos protetores podem ser de longo prazo, pois foi demonstrado que patógenos inativados pelo SODIS (diferentemente do cloro, e fervura) podem induzir alterações imunológicas que levam à geração de células B de memória de longo prazo em humanos (Ssemakalu et al., 2015; Weil et al., 2019; Chaúque et al., 2022).

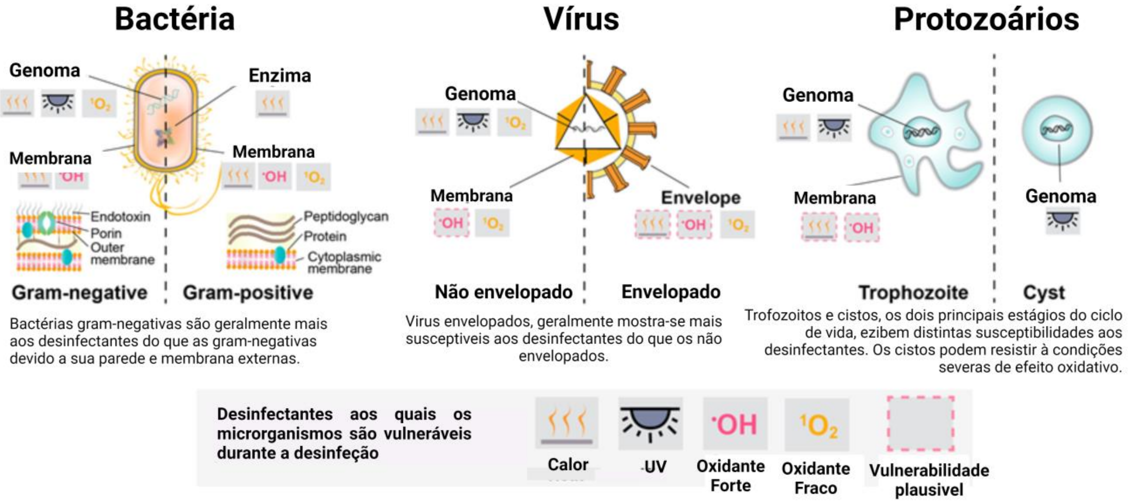
3.3.6.2 Dispositivos e sistemas de SODIS

Existe uma ampla variedade de reatores, dispositivos ou sistemas de SODIS descritos na literatura, com diferentes mecanismos de funcionamento, e as suas configurações determinam a sua produtividade (Chaúque et al., 2022a). A produtividade diária de água potável através do SODIS varia de ~1,5 L por lote a várias centenas de litros por unidade de sistema de tratamento de água (Carratalà et al., 2015; Chaúque et al., 2021b; Martínez-García et al., 2022). A menor produtividade diária de água potável (~ 1,5 – 25 L) foi relatada, especialmente no SODIS convencional em batelada (Chaúque et al., 2021a; García-Gil et al., 2022). O uso de reatores com capacidade de 88 L e 140 L também foi relatado (Reyneke et al., 2020; Martínez-García et al., 2022). Em geral, os relatos de produção de maiores volumes de água desinfetada estão associados ao uso de dispositivos ou sistemas solares de desinfecção de água. O uso de sistemas de desinfecção solar de água aprimorados dá ao SODIS o potencial para ser usado no abastecimento público de água potável em larga escala. Para isso, ainda são necessários avanços no estado da arte no desenvolvimento de sistemas SODIS de tratamento de água de fluxo intermitente ou contínuo, discutidos nos capitulos I e II (Chaúque & Rott, 2021a; Chaúque et al., 2022a).

3.3.6.3 Materiais foto-térmicos e fotocatalíticos na SODIS e na remoção de contaminantes emergentes

Grandes avanços foram feitos nas últimas décadas no campo do desenvolvimento e aplicação de nanomateriais foto-reativos (NMFR) em processos de SODIS bem como em processos de remoção de contaminantes emergentes (Huo et al., 2020). Cada vez mais, vários grupos de cientistas relatam uma variedade de novos nanomateriais e sua aplicação em distintos processos físicos, fotoelétricos, fototérmicos (NMFT), eletroporados e fotocatalíticos (NMFC). A integração dos nanomateriais foto-reativos (NMFT e NMFC) aos processos de SODIS é altamente desejável, já que o aumento significativo da temperatura e a produção de oxidantes reativos aceleram significatimente a inativação dos microrganismos (Chu et al., 2019; Figura 5, 6).

Os NMFT (por exemplo, nanopartículas de Au ou Al revestidas com SiO_2 e nanopartículas de carbono e quitosana) foram aplicados para induzir aquecimento localizado, sem ter que aquecer todo o volume de água, em poucos segundos de exposição (Gao et al., 2019; Maddigpu et al., 2018). Isso permite que um grande volume de água seja processado em batelada ou a granel, simplesmente absorvendo a radiação solar direta para obter a inativação de microrganismos (Loeb et al., 2018, Figura 5, 6).



Bactérias gram-negativas são geralmente mais aos desinfectantes do que as gram-negativas devido a sua parede e membrana externas.

Virus envelopados, geralmente mostra-se mais susceptiveis aos desinfectantes do que os não envelopados.

Trofozoitos e cistos, os dois principais estágios do ciclo de vida, ezibem distintas susceptibilidades aos desinfectantes. Os cistos podem resistir à condições severas de efeito oxidativo.

Desinfectantes aos quais os microrganismos são vulneráveis durante a desinfeção

Figura 5: Esquema da estrutura e componentes das três classes de patógenos de transmissão hídrica e sua vulnerabilidade aos mecanismos de inativação por processos de desinfecção solar integrando nanomateriais. Reproduzido de Chu et al. (2019), com permissão, Copyright© 2019, American Chemical Society.

A exposição de NMFC contidos nos reatores de SODIS à luz promove a oxidação da água e de certas substâncias nela presentes (por exemplo, desinfetantes à base de cloro), gerando oxidantes reativos (por exemplo, O_3, OH•, H_2O_2) que, por sua vez, reagem de forma rápida e indiscriminada com biomoléculas, bem como com matéria orgânica e outros solutos (Dutta et al., 2019; Patel et al 2019, Figura 6). Esta reação resulta na alteração da natureza das biomoléculas e ou substâncias presentes na água, podendo levar a uma rápida inativação de microrganismos e degradação de contaminantes químicos (por exemplo, resíduos de farmacos e defensivos agrícolas), eliminando-os da água (Bossmann et al. 1998; Kawabata et al., 2013; Remucal & Manley 2016; Chaúque & Rott, 2021a).

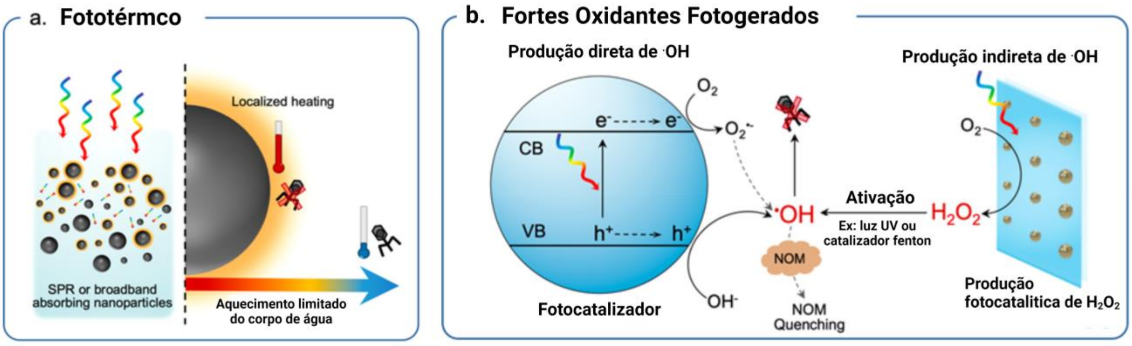


Figura 6: Esquema do mecanismo de inativação microbiana com participação de nanomateriais fototérmicos (a) e fotocatalíticos (b). Adaptado de Chu et al. (2019) com permissão, Copyright© 2019, American Chemical Society.

De modo geral, a integração de NMFC aumenta o desempenho de inativação microbiana da SODIS, e diferentes taxas de inativação microbiana e degradação de fármacos na água são relatadas na literatura. Essas taxas são influenciadas pela concentração de NMFC, a composição físico-química da água e a concentração inicial de microrganismos (Lonnen et al., 2005; Bosio et al., 2019).

4. RESULTADOS E DISCUSSÃO

Na presente tese os resultados estão organizados em nove capítulos apresentados na forma de artigos científicos publicados como primeiro autor. Outros nove artigos produzidos como primeiro autor ou em co-autoria (sem ser primeiro autor) são apresentados nos apêndices. Um pedido de depósito de patente é igualmente apresentado em apêndice X.

No capítulo I é apresentado o artigo intitulado "Prevalence of Free-Living Amoebae in Swimming Pools and Recreational Waters, a Systematic Review and Meta-Analysis" publicado em 30 de agosto de 2022 na revista Pasitology Research. https://doi.org/10.1007/s00436-022-07631-3. Este artigo faz avaliação do risco de exposição aos protozoários em diferentes corpos de água usados para recreação ao redor do mundo.

O capítulo II apresenta o artigo (carta ao Editor) intitulado "The Role of Free-Living Amoebae in the Persistence of Viruses In the Era of Severe Acute Respiratory Syndrome 2, Should We be Concerned?" publicado em 06 de junho de 2022 na revista Journal of the Brazilian Society of Tropical Medicine. https://doi.org/10.1590/0037-8682-0045-2022. Este artigo aborda sobre o papel que as amebas de vida livre (AVL) têm na manutenção e proliferação de vírus que infectam eucariontes, e sobre as possibilidades destes AVL garantirem a persistência ambiental do pandêmico vírus Sars-Cov-2 e outros virus semelhantes a este.

No Capítulo III é apresentado o artigo intitulado "Solar disinfection (SODIS) technologies as alternative for large-scale public drinking water supply: Advances and challenges" publicado em 15 de maio de 2021 na revista Chemosphere. https://doi.org/10.1016/j.chemosphere.2021.130754. Este artigo aborda sobre a necessidade, os avanços necessários, e desafios por superar para utilização das tecnologias de desinfeção solar como alternativa para o abastecimento público de água potável em larga escala.

O Capítulo IV apresenta o artigo intitulado "Development of solar water disinfection systems for large-scale public supply, state of the art, improvements and paths to the future – A systematic review" publicado em 16 de maio de 2022 na revista Journal of Environmental Chemical Engineering. https://doi.org/10.1016/j.jece.2022.107887. O artigo aborda sobre o estado da arte no desenvolvimento de sistemas de desinfeção solar de água aplicáveis no abastecimento em larga escala, e bem como as possibilidades de seu aprimoramento rumo a sistemas mais eficientes e produtivos.

No Capitulo V se apresenta o artigo intitulado "Epidemiological and Immunological Gains from Solar Water Disinfection: Fact or Wishful Thinking?" publicado em 03 agosto de 2022 na revista Tropical Medicine & International Health, https://doi.org/10.1111/tmi.13807. Este artigo aborda sobre os ganhos imunológicos e epidemiológicos, advindos da utilização da SODIS.

No capítulo VI se apresenta o artigo intitulado "Why do Low-Cost Point-Of-Use Water Treatment Technologies Succeed or Fail in Combating Waterborne Diseases in The Field? A Systematic Review" publicado na revista Journal of Environmental Chemical Engineering, http://dx.doi.org/10.1016/j.jece.2023.110575. O artigo aborda sobre os fatores que facilitam ou limitam o sucesso das intervenções para melhoria da segurança da água potável baseadas em tecnologia de baixo custo de tratamento domiciliar de água, na prevenção e combate às doenças de transmissão hídrica.

O capítulo VII apresenta o artigo intitulado "A Challenge in Washing Water with the Sun: 24 hours of SODIS Fails to Inactivate *Acanthamoeba castellanii* Cysts and Internalized *Pseudomonas aeruginosa* Under Strong Real Sun Conditions" publicado na revista Photochemical & Photobiological Sciences, http://dx.doi.org/10.1007/s43630-023-00440-2. O artigo trata da eficácia da SODIS em inativar cistos de *Acanthamoeba castellanii* e *Pseudomonas aeruginosa* abrigadas no interior dos cistos.

No capítulo VIII é apresentado o artigo "Continuous-flow solar disinfection system by boiling and ultraviolet radiation inactivating *Acanthamoeba* cysts, *Cryptosporidium* oocysts and *Bacillus* spores" publicado na resvista Journal of Environmental Chemical Engineering, http://dx.doi.org/10.1016/j.jece.2023.110074. O artigo discorre sobre o processo de aprimoramento um sistema de desinfecção solar de água em fluxo contínuo cuja eficácia foi avaliada para inativar microrganismos recalcitrantes.

No capítulo IX é apresentado o manuscrito intitulado "Preliminary insights on the development of a continuous-flow solar system for the photocatalytic degradation of contaminants of emerging concern in water" publicado a revista Environmental Science and Pollution Research, http://dx.doi.org/10.1007/s11356-024-32879-w . O artigo relata a integração de fotocatalizador no sistema de desinfecção solar de água em fluxo contínuo, e seu teste para degradar farmacose agrotóxicos na água.

CAPÍTULO I

Artigo intitulado "Prevalence of Free-Living Amoebae in Swimming Pools and Recreational Waters, a Systematic Review and Meta-Analysis" publicado na revista Pasitology Research. https://doi.org/10.1007/s00436-022-07631-3.

Prevalence of free-living amoebae in swimming pools and recreational waters, a systematic review and meta-analysis

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ABSTRACT

Free-living amoebae (FLA) are cosmopolitan microorganisms known to be pathogenic to humans who often have a history of contact with contaminated water. Swimming pools and recreational waters are among the environments where the greatest human exposure to FLA occurs. This study aimed to determine the prevalence of FLA in swimming pools and recreational waters, through a systematic review and meta-analysis that included studies published between 1977 and 2022. 106 studies were included and an overall prevalence of FLA in swimming pools and recreational waters of 44.34% (95% CI= 38.57–50.18) was found. Considering the studies published up to 2010 (1977 - 2010), between 2010 and 2015, and those published after 2010 (>2010 - 2022) the prevalence were 53.09% (95% CI= 43.33 – 62.73) and 37.07% (95% CI= 28.87 – 45.66) and 45.40% (95% CI= 35.48 – 55.51), respectively. The highest prevalence were found in the American continent (63.99 %), in Mexico (98.35 %) and in indoor hot swimming pools (52.27%). The prevalence varied with the variation of FLA detection methods, morphology (57.21%), PCR (25.78%), and simultaneously morphology and PCR (43.16%). The global prevalence by genera were *Vahlkampfia* spp. (54.20%), *Acanthamoeba* spp. (33.47%), *Naegleria* spp. (30.95%), *Hartmannella* spp. */ Vermamoeba* spp. (20.73%), *Stenamoeba* spp*.* (12.05%) and *Vannella* spp. (10.75%). There is considerable risk of FLA infection in swimming pools and recreational waters. Recreational water safety needs to be routinely monitored and, in case of risk, locations need to be identified with warning signs and users need to be educated. Swimming pools and artificial recreational water should be properly disinfected. Photolysis of NaOCl or NaCl in water by UV-C radiation is a promising alternative to disinfect swimming pools and artificial recreational waters.

Keywords: Free-living amoebae, risk of infection, swimming pool, recreational waters.

INTRODUCTION

Free-living amoebae (FLA) are cosmopolitan and ubiquitous microorganisms widely distributed in the environment and can be opportunistic and/or pathogenic (Visvesvara et al. 2007; Bellini et al. 2022). They have been isolated from many natural and anthropogenic environmental matrices, including plants, soil, air conditioning dust, bottled mineral water, drinking water treatment and distribution system, and cooling towers (Landell et al. 2013; Maschio et al. 2015; Javanmard et al. 2017; Soares et al. 2017; Wopereis et al. 2020; Pazoki et al. 2020). They have also been isolated from contact lenses, swimming pools, and other recreational waters (Fabres et al. 2016; BunsuwansakulLat et al., 2019; Santos et al. 2021; Fabros et al. 2021).

Among its representatives with importance for human health, the genera *Acanthamoeba*, *Naegleria* and *Balamuthia* stand out. *Acanthamoeba* spp., and its abundance in water bodies seems to be favored by higher temperatures (Kang et al 2020). These protozoa can cause illnesses in healthy people, such as *Acanthamoeba* keratitis (AK) which primarily affects contact lens wearers, usually due to lens wear while swimming or improper lens cleaning (Dos Santos et al. 2018). In immunosuppressed individuals, it can cause Granulomatous Amebic Encephalitis (GAE), which can be fatal (Visvesvara et al. 2007; Sarink et al. 2022). *Acanthamoeba* spp. has also been reported to cause skin infections (Murakawa et al. 1995; Paltiel et al. 2004). In addition, was isolated from 26% (17/63) of critically ill patient urine samples (Santos et al. 2009); similarly, *Acanthamoeba* (T4) was isolated from 22% (11/50) of urine samples collected from patients with recurrent urinary tract infection (Saberi et al. 2021).

Naegleria fowleri is known as a “brain-eating amoeba”, and primarily affects healthy young people using recreational waters, causing primary amoebic meningoencephalitis (PAM) (Fowler and Carter, 1965). PAM is a serious and usually fatal disease if adequate treatment is not initiated at the onset of symptoms (Król-Turmińska and Olender 2017). The rapid deterioration in the health status of patients affected by PAM, combined with the ease of being confused with bacterial meningoencephalitis (since the symptoms are similar), as well as erratic or late diagnosis, contribute to a high prevalence of deaths (> 97%) (Capewell et al. 2010; Johnson et al. 2016). *Balamuthia mandrillaris* and *Sappinia pedatta* also cause encephalitis (Gelman et al. 2001; Visvesvara et al. 2007; Cope et al. 2019) however, there are no reports of the isolation of *S. diploidea/pedatta* from swimming pools and recreational waters.

The FLA essentially have three forms of life, namely, the trophozoite form (with or without flagellum) and the flagellated form which are the active forms of the protozoan, in which it may feeds, reproduces, and expresses pathogenicity, and the form of cysts (which is the form of environmental resistance). Cysts have a double-layer wall made essentially of cellulose (Garajová et al. 2019) that protects the protozoan against unfavorable conditions (e.g., food shortages, dissection, extreme pH and temperatures) or antimicrobial agents (e.g., NaCl, chlorine, drugs, UV, heat) (Aksozek et al. 2002; Thomas et al. 2008; Chaúque and Rott 2021; Chaúque et al. 2021). FLA are considered the "Trojan Horse" of the microbial world, as phylogenetically diverse microorganisms including bacteria, fungi and viruses survive and multiply within them; these microorganisms are called amoeba-resistant microorganisms (ARM) (Greub an Raoult 2004; Scheid 2014; Delafont et al. 2016; Hubert et al. 2021; Rayamajhee et al. 2021). A wide range of pathogens of public health importance have been described as being ARM, including *Legionella pneumophila, Mycobacterium leprae, Pseudomonas* spp., *Candida auris* and various viruses (Maschio et al. 2015; Staggemeier et al. 2016; Balczun and Scheid 2017; Turankar et al. 2019; Nisar et al. 2020; Hubert et al. 2021). The participation of FLA in the environmental persistence of severe acute respiratory syndrome 2 (SARS-Cov-2) has also been proposed (Chaúque and Rott 2022; Dey et al 2022). All these aspects that characterize the profile of FLA constitute the main attributes that determine the great importance of these protozoa for human health and the environment.

Although increasingly prevalent, diseases caused by FLA remain rare; however, the presence of these protozoa, especially in the aquatic environment, is well documented (Milanez et al. 2022; Stapleton 2021; Saburi et al. 2017; Caumo et al. 2009). The presence of FLA in swimming pools and other recreational waters is of concern, as they can be pathogenic or opportunistic and/or lead to the persistence of non-amoebic pathogens in the water, including waters treated with chlorine-based disinfectants (Siddiqui and Khan 2014; Kiss et al. 2014; Dey et al. 2021). It was determined that the prevalence of *Naegleria* spp. in different water sources around the world (considering data from 35 countries) was 26.42%, in recreational water it was 21.27% (10.80 - 34.11) and in swimming pools was 44.80% (16.19 - 75.45) (Saberi et al., 2020), however, the global prevalence of FLA in swimming pools and recreational waters remains to be determined. The present systematic review and meta-analysis aimed to determine the prevalence of FLA in swimming pools and recreational waters worldwide.

METHODS

Article search strategy

The present study, which aimed to determine the prevalence of FLA in swimming pools and recreational waters, was planned and carried out based on the PRISMA 2020 guidelines (Page et al. 2021) (Fig. 1). The search for scientific articles was performed in different databases, including Web of Science, Scopus, PubMed, ScienceDirect, EMBASE, ProQuest and CAPES periódicos, between July 4 and 9, 2022. In these databases, articles were retrieved using a combination of the following search terms combined with appropriate Boolean operators: 'Free-living amoeba', 'swimming pool', 'recreational water', 'prevalence', 'epidemiology', and 'hot springs'. The references of the selected articles were examined in search of some interesting literature. The search for articles in the database was performed by B.J.M.C, and the accuracy of the searches was verified by D.L.S.

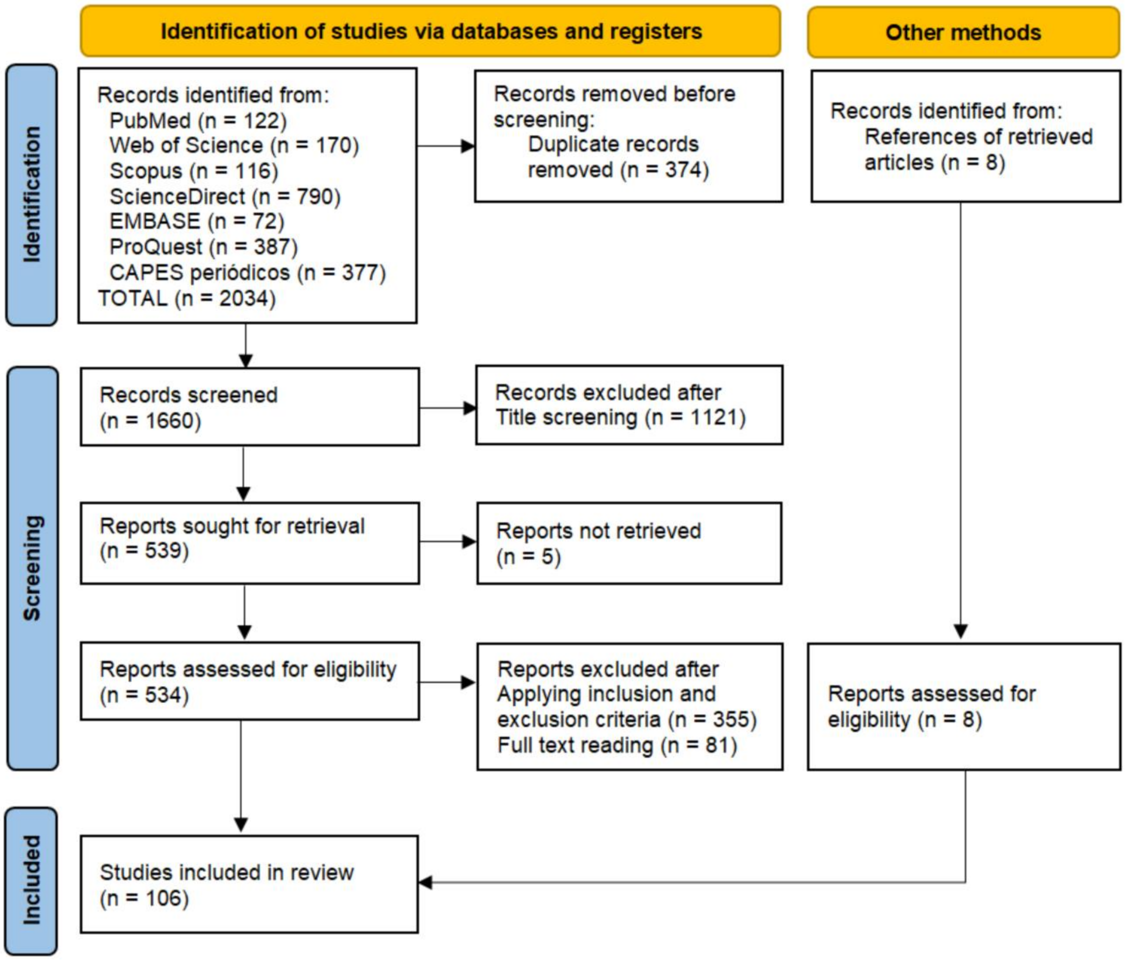

Fig. 1 Details of the article retrieval and selection steps based on PRISMA 2020.

Selection and exclusion criteria

The screening focused essentially on the title and then on the abstract of the articles. All retrieved articles written in English (reporting primary data), with accessible full text, dealing with the presence of FLA in swimming pools and human recreation waters were selected. Studies based on natural surface waters that do not clearly state that the samples were collected in places where human recreational activities certainly take place were not selected. Studies whose data were insufficient, unclear or duplicated were excluded. Case studies that do not report the prevalence of FLA in swimming pools and human recreation waters were also excluded.

Data analysis procedure

Data were independently extracted and verified by two authors (B.J.M.C and D.L.S), data verification was performed three times. Data extracted from all articles that met the inclusion criteria were included in the calculation of the global prevalence of FLA in swimming pools and recreational waters. To calculate the prevalence of each FLA genera, only data extracted from articles that included molecular methods for the identification of FLA were used. Data analysis was performed by two authors (D.A and B.J.M.C) using Stata software (version 14; Stata Corp, College Station, TX, USA) and GraphPad prism 8.02. A random-effects model meta-analysis was performed to estimate the combined and weighted prevalence of FLA in swimming pools and recreational waters, using a 95% confidence interval, and the results are visualized using a forest plot. Cochrane's Q test (chi-square) and the Higgins I^2 statistic were used to calculate the heterogeneity index among the selected studies. I^2 values <25%, 25%–50% and >50% meant low, moderate and high heterogeneity, respectively. The Egger's test was used to assess the significance of publication bias among the selected studies, $p < 0.001$ was considered significant.

RESULTS

From the total of 2,034 documents returned by the databases accessed, using the search strategy and inclusion criteria described above, 106 articles were selected (Table 1). These studies are distributed in a total of 30 countries, namely Iran (33). Taiwan (12), Egypt (8), Malaysia (6), Brazil (4), Italy (4), Turkey (4), USA (4), Mexico (3), Saudi Arabia (3), China (2), France (2), Philippines (2), Spain (2), and Thailand (2). One study was included from each of the following countries: Belgium, Bulgaria, Cape Verde, Chile, Finland, Germany, Hungary, India, Jamaica, Japan, Norway, Poland, Portugal, Sweden, and Switzerland. Among the studies, 74.52% (79/106) used or included molecular methods to identify FLA, while 25.47% (27/106) used only morphological methods.

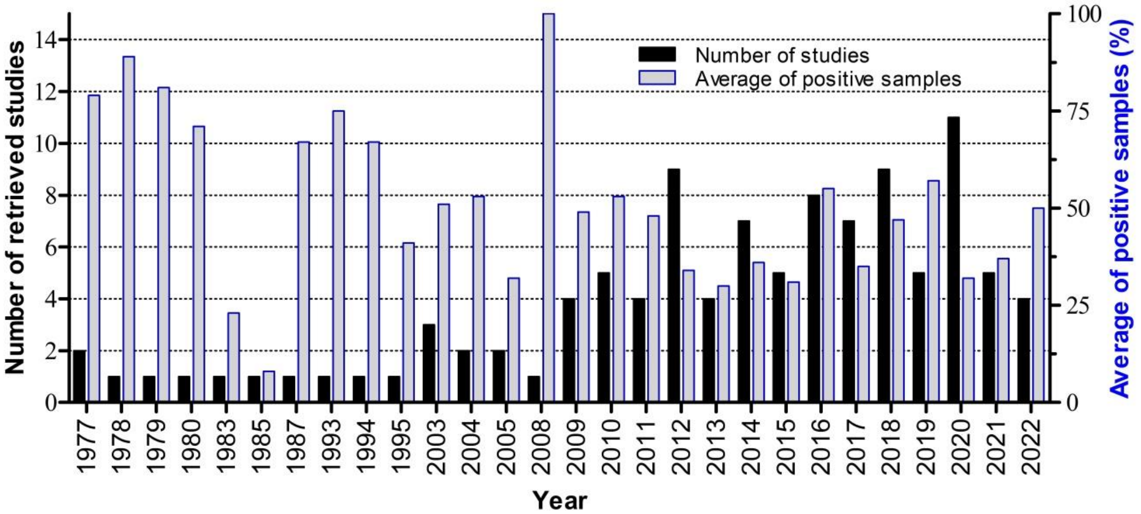

Fig. 2 Distribution of selected studies, and mean percentage of positive samples for FLA per year.

The included studies were published between 1977 and 2022, and the distribution of studies by year and the average percentage value of positive samples per year are shown in Fig. 2. FLA were detected in at least 1 sample of 97.17% (103/106) of selected studies (Table 1).

Table 1 Description of included studies reporting the prevalence of live amoebae in swimming pools and recreational waters

References	Country	Sample source (total)	Analyzed samples	Positive samples	Methods	Identity
Brown And Cursons (1977)	Norway	Swimming area	50	34	Morphology	*Acanthamoeba* spp., *Naegleria fowleri*, and *Naegleria gruberi*
Lyons and Kapur (1977)	USA	Swimming Pool	30	27	Morphology	*Acanthamoeba* spp. and /or *Hartmannella* spp.
Pernin and Riany (1978)	France	Swimming Pool (9)	44	39	Morphology	*Acanthamoeba* spp., *Hartmannella* spp., and *Naegleria* spp.
De Jonckheere (1979)	Belgium	Swimming Pool	16	13	Morphology	*Acanthamoeba* spp. and *Naegleria* spp.
Janitschke et al. (1980)	Germany	Swimming Pool	14	10	Morphology	*Acanthamoeba* spp.
Scaglia et al. 1983	Italy	Thermal pool and mud basin spa	30	7	Morphology, fluorescent-antibody technique	*N. australiensis*
Gogate and Deodhar (1985)	India	Public swimming pool	12	1	Morphology	*N. fowleri*
Scaglia et al. 1987	Italy	Thermal bath and mud basin (34)	51	34	Morphology, pathogenicity test	*Naegleria* spp., *Acanthamoeba* spp., *Vahlkampfia* spp., and *Hartmannella* spp.

Hamadto et al. 1993	Egypt	Swimming pool (16)	16	12	Morphology, pathogenicity test	*Naegleria spp.* and *Acanthamoeba* spp.
Penas-Ares et al. 1994	Spain	Thermal spa water (12)	12	8	Morphology	*Vahlkampfia longicauda*, *Vahlkampfia salina*, *Vahlkampia baltica*, *Vahlkampfia* sp., *A. polyphaga*, *Acanthamoeba lenticulata*, *Naegleria sp.*, *Lingulamoeba* sp., *Paramoeba aesturina*, and *Flabellula* sp.
Vesaluoma et al. (1995)	Finland	Public swimming pool and whirlpool (21)	34	14	Morphology	*Acanthamoeba* spp., *Vexillifera* spp., *Flabellula* spp., *Hartmannella* spp., and *Rugipes* spp.
Munoz et al. 2003	Chile	Swimming pool	8	5	Morphology, PCR	*H. vermiformes*, *Vanella* spp, *Naegleria* spp., and *Acanthamoeba* spp.
Sheehan et al. 2003	USA	Hot Spring (22)	22	12	Morphology, PCR	*N. australiensis, N. dobsoni, N. americana, N.pagei, N. polaris*, and *N. fultoni*
Izumiyama et al. 2003	Japan	Whirlpool bath and hot spring spa (251)	549	197	Morphology, PCR	*N. fowleri, N. lovaniensis*, and *N. australiensis*
Górnik and Kuźna-Grygiel (2004)	Poland	Public swimming pools (13)	72	42	Morphology	*Acanthamoeba* spp.
Tsvetkova et al. 2004	Bulgaria	Swimming pool (6)	31	15	Morphology, PCR	*Acanthamoeba* spp., and *Hartmannella* spp
Lekkla et al. (2005)	Thailand	Hot spring (13)	68	26	Morphology	*Acanthamoeba* spp. and *Naegleria* spp.
Sukthana et al. 2005	Thailand	Hot spring	57	15	Morphology	*Naegleria* spp. and *Acanthamoeba* spp.
Rezaeian et al 2008	Iran	Swimming pool	2	2	Morphology	*Acanthamoeba* spp.
Caumo et al. (2009)	Brazil	Swimming pool	65	13	Morphology, PCR	*Acanthamoeba* spp.
Gianinazzi et al. (2009)	Switzerland	Indoor hot swimming pool	1	1	Morphology, PCR	*Acanthamoeba lenticulata*
Hsu et al. (2009)	Taiwan	Recreational hot spring	55	9	PCR	*Acanthamoeba griffini* and *Acanthamoeba jacobsi*
Hsu et al. (2009a)	Taiwan	Mud recreation area water	34	20	Morphology, PCR	*Acanthamoeba* spp., *Hartmannella* spp., and *Naegleria* spp.
Gianinazzi et al. (2010)	Sweden	Hot springs (4)	31	9	Morphology, PCR	*Acanthamoeba healyi, Stenoamoeba* sp., *Hartmannella vermiformis*, and *Echinamoeba exundans*
Huang and Hsu (2010)	Taiwan	Hot spring and waste water in recreation area	52	11	PCR	*Acanthamoeba* T1, *Acanthamoeba* T2, *Acanthamoeba* T3, *Acanthamoeba* T4, *Acanthamoeba* T5, *Acanthamoeba* T6, and

						Acanthamoeba T15
Huang and Hsu (2010a)	Taiwan	Hot spring and hot spring facilities	106	15	Morphology, PCR	*Naegleria lovaniensis, Naegleria australiensis, Naegleria clarki, Naegleria americana*, and *Naegleria pagei*
Init et al. (2010)	Malaysia	Public swimming pool (14)	14	14	Morphology	*Acanthamoeba* spp. and *Naegleria* spp.
Lares-Villa et al. 2010	Mexico	Natural Recreational water (2)	24	24	PCR	Thermophilic amoebae, Thermophilic *Naegleria* spp., and *N. fowleri*
Badirzadeh et al. (2011)	Iran	Recreational hot spring	28	12	Morphology, PCR	*Vahlkampfiid* and *Acanthamoeba castellanii* T4
Huang and Hsu (2011)	Taiwan	Recreational water	107	19	PCR	*Naegleria* spp.
Ithoi et al. (2011)	Malaysia	Recreational pool, lake and stream	33	33	Morphology, PCR	*Naegleria* spp.
Nazar et al. 2011	Iran	Water in recreation area	50	16	Morphology, PCR	*Acanthamoeba* spp. T4 and *Acanthamoeba* spp. T5
Alves et al. (2012)	Brazil	Public swimming pool (7)	7	7	Morphology, PCR	*Acanthamoeba* spp.
Kao et al. (2012)	Taiwan	Recreation and drinking water source (2)	211	13	PCR	*Naegleria philippinensis*, *N. clarki*, *Naegleria gálica*, *N. americana*, *N. australiensis*, *Naegleria dobsoni*, *N. gruberi*, and *Naegleria schusteri*
Kao et al. (2012a)	Taiwan	Recreational hot spring (4)	60	9	Morphology, PCR	*Acanthamoeba* T15*,* *Acanthamoeba* T4*,* *Acanthamoeba* T2, and *Acanthamoeba* spp.
Kao et al. (2012b)	Taiwan	Hot spring	60	26	Morphology, PCR	*N. australiensis,* *N. lovaniensis*, *Naegleria Mexicana*, and *N. gruberi*
Nazar et al. (2012)	Iran	Recreational water (22)	50	8	Morphology, PCR	*Hartmannella vermiformis* and *Vannella persistens*
Niyyati et al. (2012)	Iran	River recreation area (10)	55	15	Morphology, PCR	*Acanthamoeba* spp. (T4 e T15) and *Naegleria* spp. (*N. pagei, N. clarki*, and *Naegleria fultoni*)
Rahdar et al. 2012	Iran	Swimming pool (4)	4	2	Morphology, PCR	*Acanthamoeba* T4
Solgi et al. (2012)	Iran	Hot spring	30	8	Morphology, PCR	*Hartmannella vermiformis and* *Naegleria* (*N. carteri*, and *Naegleria* spp.)
Solgi et al. (2012a)	Iran	Therapeutic hot spring	60	12	Morphology, PCR	*Acanthamoeba* T4 and T3
Kao et al. 2013	China	Thermal spring water	48	4	PCR	*Naegleria* spp.
Kao et al. 2013a	China	Thermal spring	48	5	PCR	*Acanthamoeba* spp.
Moussa et al. (2013)	France	Recreational geothermal waters(6)	73	35	Morphology, PCR	*N. fowleri* and *N. lovaniensis*
Tung et al.	Taiwan	Hot spring (1)	25	13	Morphology,	*Naegleria* spp. *(N.*

(2013)					PCR	*fowleri)* and *Acanthamoeba* spp.
Al-Herrawy et al. (2014)	Egypt	Swimming pool (10)	120	59	Morphology, PCR	*Acanthamoeba* spp.
Ji et al. (2014)	Taiwan	Hot spring	61	29	Morphology, PCR	*Acanthamoeba* spp.
Ji et al. (2014)	Taiwan	Hot spring	61	17	Morphology, PCR	*Naegleria* spp.
Ji et al. (2014)	Taiwan	Hot spring	61	11	Morphology, PCR	*Vermamoeba vermiformis*
Kiss et al. (2014)	Hungary	Swimming pool (20)	164	68	Morphology, PCR	*Acanthamoeba* spp.
Onichandran et al. 2014	Philippines	Recreational river (4)	23	12	Morphology, PCR	*Acanthamoeba* spp. and *Naegleria* spp.
Sifuentes et al. (2014)	USA	Recreational water (33)	103	18	PCR	Thermophilic amoebae and *N. fowleri*
Behniafar et al. (2015)	Iran	Recreational water and hot spring	40	7	Morphology, PCR	*Acanthamoeba* spp.
Evyapan et al. (2015)	Turkey	Swimming pool and hot spring	50	21	Morphology, PCR	*Acanthamoeba* spp., *Acanthamoeba griffini T3*, *Acanthamoeba castellanii* T4, and *A. jacobsi* T15
Niyyati et al. (2015)	Iran	Recreational water (lakes, pools and streams)	60	9	Morphology, PCR	*N. australiensis* and *N. pagei*
Niyyati et al. (2015a)	Iran	Recreational water	50	15	Morphology, PCR	*A. castellanii* T4
Todd et al. (2015)	Jamaica	Recreational water	83	42	Morphology, PCR	*Acanthamoeba* T4, *Acanthamoeba* T5, *Acanthamoeba* T10, and *Acanthamoeba* T11
Al-Herrawy et al. (2016)	Egypt	Swimming pool (1)	48	30	Morphology, PCR	*Acanthamoeba* spp., *Naegleria* spp., and *Hartmannella*
Armand et al. (2016)	Iran	Swimming pool	17	12	Morphology, PCR	*Vermamoeba* spp. and *Acanthamoeba* spp.
Azlan et al. 2016	Malaysia	Recreational lake	7	7	Morphology	*Acanthamoeba* spp.
Fabres et al. (2016)	Brazil	Hot tubs and thermal pool	72	20	Morphology, PCR	*Acanthamoeba* T3, *Acanthamoeba* T4, *Acanthamoeba* T5, and *Acanthamoeba* T15
Latifi et al. (2016)	Iran	Hot spring	66	2	Morphology, PCR	*Balamuthia mandrillaris*
Niyyati et al. (2016)	Iran	Geothermal water source	40	20	PCR	*Acanthamoeba* T4 and T2
Niyyati et al. (2016a)	Iran	Recreational water	25	25	Morphology	Vahlkampfidae spp., *Acanthamoeba* spp., Thecamoeba spp., and *Miniamoebae* spp.
Al-Herrawy et al. (2017)	Egypt	Swimming pool (2)	144	37	Morphology, PCR	*Acanthamoeba* spp. and *Naegleria* spp.
Di Filippo et al. (2017)	Italy	Geothermal spring	36	26	Morphology, PCR	*N. australiensis*, *Naegleria itálica*, *N. lovaniensis*, and *Naegleria* spp.
Javanmard et	Iran	Swimming pool	33	6	Morphology,	*N. pagei* and *N. gruberi*

al. (2017)		and hot spring			PCR	
Latifi et al. (2017)	Iran	Recreation hot spring	22	12	Morphology, PCR	*Naegleria* spp. (*N. australiensis, N. americana, N. dobsoni, N. pagei, N. polaris*, and *N. fultoni*)
Mafi et al. (2017)	Iran	Swimming pool and park pond (40)	75	18	Morphology	*Acanthamoeba* spp*.*, *Hartmannella* spp., and *Vahlkampfiids*
Reyes-Batlle et al. (2017)	Spain	Recreational water (10)	10	1	Morphology, PCR	*Naegleria* spp.
Toula and Elahl 2017	Saudi Arabia	Swimming pool (6)	16	6	Morphology	*Acanthamoeba* spp. and *Naegleria spp.*
Dodangeh et al. (2018)	Iran	Recreational hot spring	24	11	Morphology, PCR	*Acanthamoeba castellanii* T4
Ghaderifar et al. 2018	Iran	Parks pond water (13)	90	31	Morphology, PCR	*Acanthamoeba* T4
Hikal et al (2018)	Egypt	Swimming pool (5)	100	24	Morphology, PCR	*Naegleria fowleri*
Hikal et al. (2018)	Egypt	Swimming pool (5)	100	79	Morphology, PCR	*Naegleria* spp.
Lares-Jiménez et al. (2018)	Mexico	Hot spring (1)	8	8	Morphology, PCR	*N. lovaniensis, A. jacobsi, Stenamoeba sp.*, and *Vermamoeba vermiformis*
Latiff et al. (2018)	Malaysia	Recreational hot spring (5)	52	38	Morphology	*Acanthamoeba* spp. and *Naegleria spp.*
Poor et al. (2018)	Iran	Swimming pool and hot tubs (10)	40	8	Morphology, PCR	*Acanthamoeba* T3 and *Acanthamoeba* T4
Vijayakumar (2018)	Saudi Arabia	Pools and recreation waters	27	7	Morphology	*Acanthamoeba* spp.
Xue et al. 2018	USA	lake recreation areas (10)	160	56	PCR	*N. fowleri*
Gabriel et al. 2019	Malaysia	Recreational place	57	40	Morphology, PCR	*Acanthamoeba* spp. and *Naegleria* spp.
Haddad et al. (2019)	Iran	Hot springs	54	15	Morphology, PCR	*Acanthamoeba castellanii* T4, *Vermamoeba vermiformis*, *N. australiensis, N. pageii,* and *N. gruberi*
Hussain et al. (2019)	Malaysia	Recreational hot spring (5)	50	38	Morphology, PCR	*Acanthamoeba* T4, T15, T3, T5, T11 and T17
Maghsoodloo rad et al. 2019	Iran	Recreational park water	30	8	Morphology, PCR	*Acanthamoeba* spp. T4 and *Acanthamoeba* spp. T15
Salehi et al. 2019	Iran	Park pool and Swimming pool	14	12	Morphology, PCR	*Acanthamoeba* T2, T4, T5, and T11
Attariani et al. (2020)	Iran	Swimming pool	42	3	Morphology, PCR	*Acanthamoeba* spp.
Ballares et al. 2020	Philippines	Recreational water (6)	16	6	Morphology, PCR	*Acanthamoeba* T4, *Acanthamoeba* T5, and *Acanthamoeba* T9
Bonilla-Lemus et al. 2020	Mexico	Recreational water (9)	9	9	Morphology, PCR	*N. australiensis*, *N. gruberi*, *N. fowleri*, *N. clarki,* and *N. pagei*
Değerli et al. (2020)	Turkey	Thermal swimming pool	434	148	Morphology, PCR	*Acanthamoeba* spp. and *Naegleria* spp.
El-Badry et al. 2020	Egypt	Swimming pool (7)	28	0	Morphology, PCR	

Esboei et al. (2020)	Iran	Swimming pools	30	12	Morphology, PCR	*Acanthamoeba* T4
Latifi et al. (2020)	Iran	Hot spring and beach	81	54	Morphology, PCR	*Acanthamoeba* (T3, T4 e T5), *V. vermiformis,* and *Naegleria* spp.
Paknejad et al. (2020)	Iran	Swimming pool and bathtub	166	31	Morphology, PCR	*Acanthamoeba* T3, *Acanthamoeba* T4, *Acanthamoeba* T11, *Acanthamoeba* sp., *Protacanthamoeba bohemica, and N. lovaniensis*
Sarmadian et al. (2020)	Iran	Swimming pool (6)	6	1	Morphology	*Acanthamoeba* spp.
Sarmadian et al. (2020)	Iran	Swimming pool (6)	576	1	Morphology	*Acanthamoeba* spp.
Zeybek and Türkmen 2020	Turkey	Swimming pool	25	7	Morphology, FISH	
Aykur and Dagci (2021)	Turkey	Swimming pool	26	3	PCR	*Acanthamoeba* T2, T4 and T5
Bakri et al. 2021	Saudi Arabia	Swimming pool	10	4	Morphology, PCR	*Acanthamoeba* spp. and *Naegleria* spp.
Berrilli et al. (2021)	Italy	Hot Spring (2)	36	33	Morphology, PCR	*V. vermiformisi,* *N. australiensisi,* *Acanthamoeba* T4*,* and *Acanthamoeba* T15
Eftekhari-Kenzerki et al. (2021)	Iran	Indoor public swimming pool (20)	80	32	Morphology, PCR	*Acanthamoeba* spp.
Reyes-Batlle et al. (2021)	Portugal	Swimming pool facilities (20)	20	0	PCR	
Nageeb et al. (2022)	Egypt	Swimming pool (2)	8	0	Morphology, PCR	
Rocha et al. 2022	Brazil	Swimming pool (9)	36	15	Morphology	*Acanthamoeba* spp. and *Naegleria* spp.
Salehi et al. 2022	Iran	Swimming pool and Park pool	20	17	Morphology, PCR	*Acanthamoeba* (T2, T3, T4, T11 and T15)
Sousa-Ramos et al. 2022	Cape Verde	Recreational fountain and Swimming pool	4	2	Morphology, PCR	*Acanthamoeba* sp. T4 and *Vannella* sp.

Publication bias was checked by Egger's regression test, showed that it may have a substantial impact on total prevalence estimate (Egger; bias: 6.8, P < 0.001) (Fig. 3). This suggests that the reported global prevalence may have been impacted by publication bias.

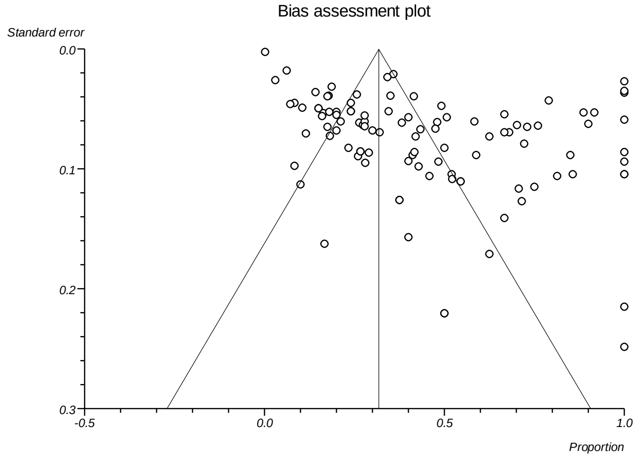

Fig. 3 Result of Egger's bias assessment for the prevalence of free-living amoebae in swimming pools and recreational waters.

Based on the random-effects model meta-analysis, the pooled prevalence of FLA in water sources was 44.34% (95% CI= 38.57– 50.18). The included studies demonstrated a strong heterogeneity (Q= 2198.0, df= 102, I^2= 95.4%, P<0.0001) (Fig. 4).

The global prevalence of FLA in swimming pools and recreational waters considering studies published up to 2010 (1977-2010) was considerably higher 53.09% (95% CI = 43.33 – 62.73) than in studies published between 2010 and 2015, 37.07% (95% CI = 28.87 – 45.66), and those published after 2015 (>2015-2022) 45.40% (95% CI = 35.48 – 55.51) (Table 2).

Considering the continents covered by the selected studies, the highest prevalence 63.99% (95% CI = 45.03 – 80.92) was reported in America and the lowest 37.38% (95% CI = 30.12 – 44.93) in Asia. Among the countries from which more than one study was included, Mexico had the highest prevalence of FLA in swimming pools and recreational waters 98.35% (95% CI = 92.56 – 99.96), and the lowest prevalence 10.15% (95% CI = 4.99 – 16.87) was recorded in China (Table 2).

Considering the different sampling sources, the highest prevalence of FLA 52.27% (95% CI = 14.55– 88.50) was obtained in Indoor hot swimming pools, and the lowest prevalence 39.12% (95% CI = 30.48 – 48.13) was obtained in hot springs (Table 2).

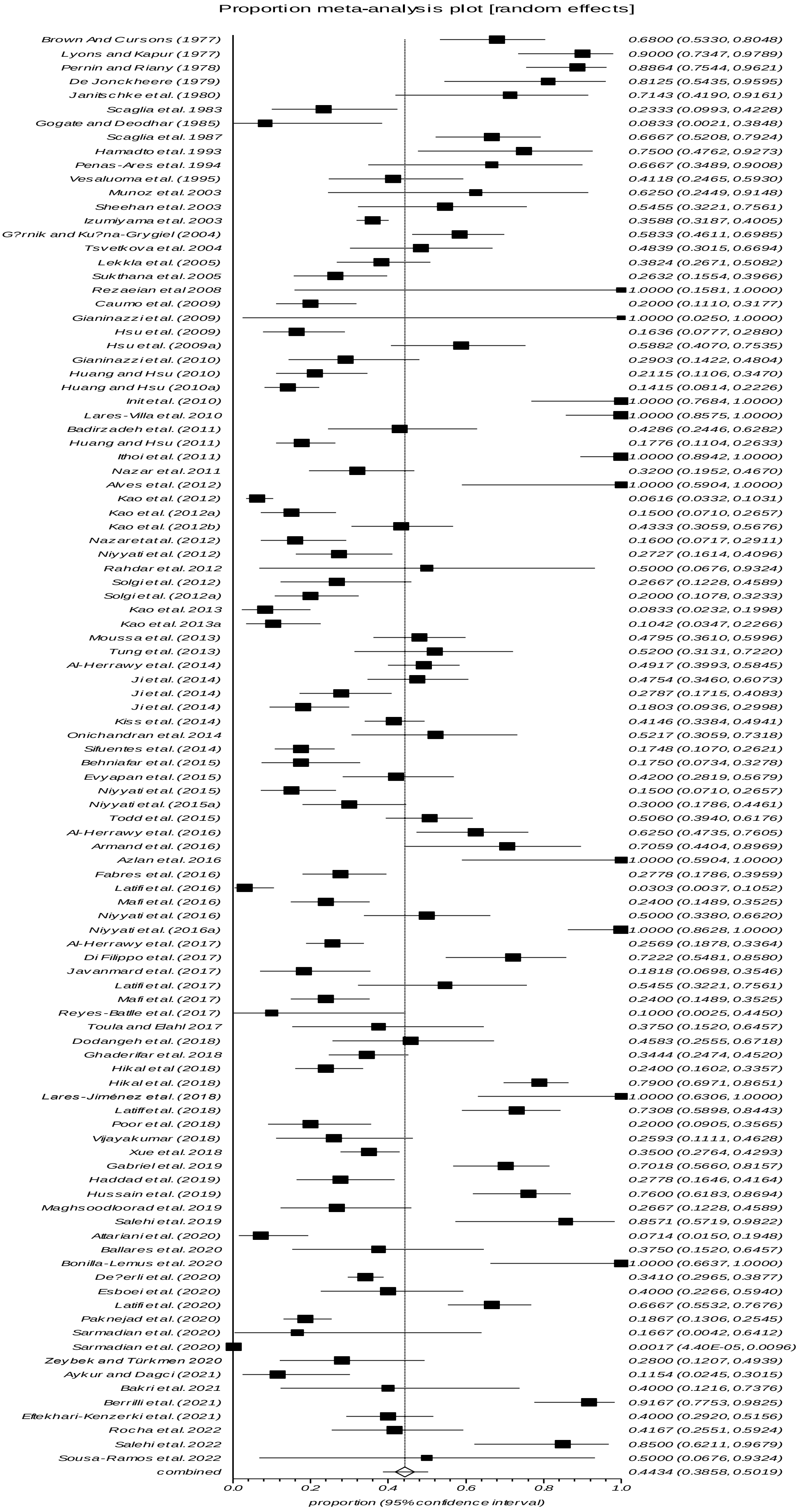
Proportion meta-analysis plot [random effects]
Brown And Cursons (1977) 0.6800 (0.5330, 0.8048)
Lyons and Kapur (1977) 0.9000 (0.7347, 0.9789)
Pernin and Riany (1978) 0.8864 (0.7544, 0.9621)
De Jonckheere (1979) 0.8125 (0.5435, 0.9595)
Janitschke et al. (1980) 0.7143 (0.4190, 0.9161)
Scaglia et al. 1983 0.2333 (0.0993, 0.4228)
Gogate and Deodhar (1985) 0.0833 (0.0021, 0.3848)
Scaglia et al. 1987 0.6667 (0.5208, 0.7924)
Hamadto et al. 1993 0.7500 (0.4762, 0.9273)
Penas-Ares et al. 1994 0.6667 (0.3489, 0.9008)
Vesaluoma et al. (1995) 0.4118 (0.2465, 0.5930)
Munoz et al. 2003 0.6250 (0.2449, 0.9148)
Sheehan et al. 2003 0.5455 (0.3221, 0.7561)
Izumiyama et al. 2003 0.3588 (0.3187, 0.4005)
G?rnik and Ku?na-Grygiel (2004) 0.5833 (0.4611, 0.6985)
Tsvetkova et al. 2004 0.4839 (0.3015, 0.6694)
Lekkla et al. (2005) 0.3824 (0.2671, 0.5082)
Sukthana et al. 2005 0.2632 (0.1554, 0.3966)
Rezaeian et al 2008 1.0000 (0.1581, 1.0000)
Caumo et al. (2009) 0.2000 (0.1110, 0.3177)
Gianinazzi et al. (2009) 1.0000 (0.0250, 1.0000)
Hsu et al. (2009) 0.1636 (0.0777, 0.2880)
Hsu et al. (2009a) 0.5882 (0.4070, 0.7535)
Gianinazzi et al. (2010) 0.2903 (0.1422, 0.4804)
Huang and Hsu (2010) 0.2115 (0.1106, 0.3470)
Huang and Hsu (2010a) 0.1415 (0.0814, 0.2226)
Init et al. (2010) 1.0000 (0.7684, 1.0000)
Lares-Villa et al. 2010 1.0000 (0.8575, 1.0000)
Badirzadeh et al. (2011) 0.4286 (0.2446, 0.6282)
Huang and Hsu (2011) 0.1776 (0.1104, 0.2633)
Ithoi et al. (2011) 1.0000 (0.8942, 1.0000)
Nazar et al. 2011 0.3200 (0.1952, 0.4670)
Alves et al. (2012) 1.0000 (0.5904, 1.0000)
Kao et al. (2012) 0.0616 (0.0332, 0.1031)
Kao et al. (2012a) 0.1500 (0.0710, 0.2657)
Kao et al. (2012b) 0.4333 (0.3059, 0.5676)
Nazaretatal. (2012) 0.1600 (0.0717, 0.2911)
Niyyati et al. (2012) 0.2727 (0.1614, 0.4096)
Rahdar et al. 2012 0.5000 (0.0676, 0.9324)
Solgi et al. (2012) 0.2667 (0.1228, 0.4589)
Solgi et al. (2012a) 0.2000 (0.1078, 0.3233)
Kao et al. 2013 0.0833 (0.0232, 0.1998)
Kao et al. 2013a 0.1042 (0.0347, 0.2266)
Moussa et al. (2013) 0.4795 (0.3610, 0.5996)
Tung et al. (2013) 0.5200 (0.3131, 0.7220)
Al-Herrawy et al. (2014) 0.4917 (0.3993, 0.5845)
Ji et al. (2014) 0.4754 (0.3460, 0.6073)
Ji et al. (2014) 0.2787 (0.1715, 0.4083)
Ji et al. (2014) 0.1803 (0.0936, 0.2998)
Kiss et al. (2014) 0.4146 (0.3384, 0.4941)
Onichandran et al. 2014 0.5217 (0.3059, 0.7318)
Sifuentes et al. (2014) 0.1748 (0.1070, 0.2621)
Behniafar et al. (2015) 0.1750 (0.0734, 0.3278)
Evyapan et al. (2015) 0.4200 (0.2819, 0.5679)
Niyyati et al. (2015) 0.1500 (0.0710, 0.2657)
Niyyati et al. (2015a) 0.3000 (0.1786, 0.4461)
Todd et al. (2015) 0.5060 (0.3940, 0.6176)
Al-Herrawy et al. (2016) 0.6250 (0.4735, 0.7605)
Armand et al. (2016) 0.7059 (0.4404, 0.8969)
Azlan et al. 2016 1.0000 (0.5904, 1.0000)
Fabres et al. (2016) 0.2778 (0.1786, 0.3959)
Latifi et al. (2016) 0.0303 (0.0037, 0.1052)
Mafi et al. (2016) 0.2400 (0.1489, 0.3525)
Niyyati et al. (2016) 0.5000 (0.3380, 0.6620)
Niyyati et al. (2016a) 1.0000 (0.8628, 1.0000)
Al-Herrawy et al. (2017) 0.2569 (0.1878, 0.3364)
Di Filippo et al. (2017) 0.7222 (0.5481, 0.8580)
Javanmard et al. (2017) 0.1818 (0.0698, 0.3546)
Latifi et al. (2017) 0.5455 (0.3221, 0.7561)
Mafi et al. (2017) 0.2400 (0.1489, 0.3525)
Reyes-Batlle et al. (2017) 0.1000 (0.0025, 0.4450)
Toula and Elahl 2017 0.3750 (0.1520, 0.6457)
Dodangeh et al. (2018) 0.4583 (0.2555, 0.6718)
Ghaderifar et al. 2018 0.3444 (0.2474, 0.4520)
Hikal et al (2018) 0.2400 (0.1602, 0.3357)
Hikal et al. (2018) 0.7900 (0.6971, 0.8651)
Lares-Jiménez et al. (2018) 1.0000 (0.6306, 1.0000)
Latiff et al. (2018) 0.7308 (0.5898, 0.8443)
Poor et al. (2018) 0.2000 (0.0905, 0.3565)
Vijayakumar (2018) 0.2593 (0.1111, 0.4628)
Xue et al. 2018 0.3500 (0.2764, 0.4293)
Gabriel et al. 2019 0.7018 (0.5660, 0.8157)
Haddad et al. (2019) 0.2778 (0.1646, 0.4164)
Hussain et al. (2019) 0.7600 (0.6183, 0.8694)
Maghsoodloorad et al. 2019 0.2667 (0.1228, 0.4589)
Salehi et al. 2019 0.8571 (0.5719, 0.9822)
Attariani et al. (2020) 0.0714 (0.0150, 0.1948)
Ballares et al. 2020 0.3750 (0.1520, 0.6457)
Bonilla-Lemus et al. 2020 1.0000 (0.6637, 1.0000)
De?erli et al. (2020) 0.3410 (0.2965, 0.3877)
Esboei et al. (2020) 0.4000 (0.2266, 0.5940)
Latifi et al. (2020) 0.6667 (0.5532, 0.7676)
Paknejad et al. (2020) 0.1867 (0.1306, 0.2545)
Sarmadian et al. (2020) 0.1667 (0.0042, 0.6412)
Sarmadian et al. (2020) 0.0017 (4.40E-05, 0.0096)
Zeybek and Türkmen 2020 0.2800 (0.1207, 0.4939)
Aykur and Dagci (2021) 0.1154 (0.0245, 0.3015)
Bakri et al. 2021 0.4000 (0.1216, 0.7376)
Berrilli et al. (2021) 0.9167 (0.7753, 0.9825)
Eftekhari-Kenzerki et al. (2021) 0.4000 (0.2920, 0.5156)
Rocha et al. 2022 0.4167 (0.2551, 0.5924)
Salehi et al. 2022 0.8500 (0.6211, 0.9679)
Sousa-Ramos et al. 2022 0.5000 (0.0676, 0.9324)
combined 0.4434 (0.3858, 0.5019)
0.0
0.2
0.4
0.6
0.8
1.0
proportion (95% confidence interval)

Fig. 4 Forest plot of the worldwide prevalence of free-living amoebae in swimming pools and recreational waters.

The analysis of data from studies that used only morphological methods to identify FLA showed the highest prevalence 57.21% (95% CI = 37.99 – 7535), the lowest prevalence 25.78% (95% CI = 14.18 – 39.44) was obtained from studies based only on molecular methods (PCR), an intermediate prevalence value 43.16% (95% CI = 37.73 – 48.67) was obtained by analyzing studies that simultaneously used morphological and molecular methods (Table 2).

The subgroup analysis revealed that there were statistically significant differences between the overall prevalence of FLA in water sources and year (X^2= 449.4, P < 0.001), continent (X^2= 156.7, P < 0.001), country (X^2= 26.0, P < 0.001) and diagnostic method (X^2= 373.5, P < 0.001) (Table 2).

Table 2 Subgroup analysis of FLA in water sources

Subgroup variable	**Prevalence (95% CI)**	**I^2 (%)**	**Heterogeneity (*Q*)**	**P-value**	**Interaction test (X^2)**	**P-value**
Year						
<2010	53.09 (43.33 – 62.73)	89.5%	210.4	P < 0.001	449.4	P < 0.001
2010-2015	37.07 (28.87 – 45.66)	93.6%	519.5	P < 0.001		
> 2015	45.40 (35.48 – 55.51)	96.7%	1366.2	P < 0.001		
Continent						
Africa	51.27 (35.08 – 67.33)	93.5%	107.8	P < 0.001	156.7	P < 0.001
America	63.99 (45.03 – 80.92)	94.5%	201.7	P < 0.001		
Asia	37.38 (30.12 – 44.93)	95.7%	1403.3	P < 0.001		
Europe	51.99 (42.52 – 61.40)	89.5%	190.6	P < 0.001		
Country						
Brazil	43.70 (21.99 – 66.76)	88.7%	26.5	P < 0.001	26.0	P < 0.001
China	10.15 (4.99 – 16.87)	-	0.1	P = 0.737		
Egypt	51.65 (31.74 – 71.30)	95.3%	107.0	P < 0.001		
France	69.62 (27.07 – 97.94)	-	22.5	P < 0.001		
Iran	35.11 (24.74 – 46.26)	95.9%	787.8	P < 0.001		
Italy	64.76 (37.01 – 87.95)	92.1%	38.2	P < 0.001		
Malaysia	87.38 (73.20 – 96.72)	85%	33.3	P < 0.001		
Mexico	98.35 (92.56 – 99.96)	0%	0.1	P = 0.913		
Philippines	46.29 (31.43 – 61.48)	-	0.7	P = 0.377		
Saudi Arabia	32.85 (21.28 – 45.60)	0%	1.0	P = 0.602		
Spain	37.68 (1.06 – 88.08)	-	7.7	P = 0.005		
Taiwan	26.33 (17.36 – 36.42)	90.6%	116.4	P < 0.001		
Thailand	32.68 (21.82 – 44.57)	-	1.9	P = 0.160		
Turkey	30.60 (20.92 – 41.23)	65.6%	8.7	P = 0.033		
USA	48.70 (22.32 – 75.47)	95.3%	63.7	P < 0.001		

Origin						
Hot springs	39.12 (30.48 – 48.13)	93%	369.0	P < 0.001	51.6	P = 0.224
Indoor hot swimming pools	52.27 (14.55– 88.50)	-	1.8	P = 0.169		
Public swimming pools	49.47 (36.87– 62.10)	97%	1201.5	P < 0.001		
Recreational waters	44.44 (33.19– 55.99)	95%	538.7	P < 0.001		
Thermal swimming pools	46.05 (2674– 65.99)	88.8%	26.7	P < 0.001		
Diagnostic method						
Morphology	57.21 (37.99 – 7535)	97.8%	1083.3	P < 0.001	373.5	P < 0.001
PCR	25.78 (14.18 – 39.44)	94.6%	183.6	P < 0.001		
Morphology and PCR	43.16 (37.73 – 48.67)	91.6%	757.6	P < 0.001		

The highest values of the global prevalence of different genera of FLA in swimming pools and recreational waters were from *Vahlkampfia* spp. (54.20%), *Acanthamoeba* spp. (33.47%) and *Naegleria* spp. (30.95%). For other genera, *Hartmannella* spp. **/** *Vermamoeba* spp., *Stenamoeba* spp., and *Vannella* spp. the global prevalence values were 20,73%, 12.05% and 10.75%, respectively (Table 3). The results of Egger's regression test, as well as the forest plot of the worldwide prevalence of each of these FLA genera in swimming pools and recreational waters can be seen in Fig. S1, S2, S3, S4, S5, and S6 of the supplementary material, respectively.

Table 3 Global prevalence, publication bias, and heterogeneity of FLA in water sources

Genus	Prevalence, % (95% CI)	Cochran Q	df	I² (%)	P-value	Egger bias	P-value
***Acanthamoeba* spp.**	33.47 (28.06 – 39.11)	429.1	55	87.2%	< 0.001	3.4	0.0002
***Hartmannella* spp. / *Vermamoeba* spp.**	20.73 (7.73 – 38.39)	30.55	5	83.8%	0.0008	5.9	0.1363
***Naegleria* spp.**	30.95 (22.85 – 39.69)	676.0	38	94.4%	< 0.001	4.6	0.0054
Stenamoeba spp.	12.05 (0.08 – 39.61)	3.2	1	-	0.0732	-	-
***Vahlkampfia* spp.**	54.20 (27.49 – 79.67)	12.6	2	84.2%	0.0018	-	-
***Vannella* spp.**	10.75 (0.01 – 37.14)	2.2	1	-	0.133	-	-

CI: confidence interval; df: degree of freedom.

DISCUSSION

FLA are cosmopolitan microorganisms ubiquitous in all matrices of natural and anthropogenic environments, including water resources. The presence of FLA in pools and recreational waters is worrying, since some of these microorganisms are human pathogens/opportunists, as well as being widely implicated in persistence and / or pseudo-resistance of pathogenic bacteria, viruses, and fungi in water, including in water treated with disinfectants

(Thomas et al. 2004; Staggemeier et al. 2016; Mavridou et al. 2018; Gomes et al. 2020; Hubert et al. 2021).

The studies included in present review are distributed by five continents, however, they have a heterogeneous spatial distribution within the territories of the continents, this can suggest differences in the level of FLA importance for health in the contexts of different countries, as well as differences in the frequency of cases diseases associated with the FLA. The frequency of cases of FLA related diseases can be influenced by the difference in the predominance of risk factors, the sensitivity of the health surveillance strategy of each country, as well as the heterogeneous distribution of trained professionals carrying out research in this area. In addition, the ease of confusing symptoms of diseases associated with the FLA with those caused by other microorganisms, combined with some cases of rapid deterioration of the patient's health and death (Jahangéer et al. 2020) can contribute to the rarity of reports or even the lack of association of diseases with FLA, especially in contexts where post-mortem study policies are not robust.

Our findings show that the global prevalence of FLA in swimming pools and recreational waters is 44.34%, however, a higher (53.09%) and intermediate (45.40%) prevalence value was obtained when considering the data from studies published up to 2010 and studies published after 2015, respectively. A lower prevalence value (37.07%) was obtained when analyzing data from studies published between 2010 and 2015 (Table 2). A similar result was reported in a study that aimed to determine the prevalence of *Naegleria* spp. in water resources (Saberi et al. 2020). This reduction in the prevalence reported in most recent studies was attributed to the most accurate diagnosis and reduction of false positive results (Jahangeeer et al. 2020; Saberi et al. 2020), as contrary to studies published up to 2010, the vast majority of studies published after 2010 used molecular methods for FLA identification. Curiously, our results show that the overall prevalence of FLA considering studies that used both morphological and molecular methods is close to the mean of the prevalence values obtained from data from studies that used only one of the methods (Table 2). This may suggest that the simultaneous use of these two methods reduces the extreme values obtained separately by each of the methods, and that these methods can be complementary, especially in studies that aim to assess the presence or absence of viable FLA in water samples. The authors agree that the morphological method (generally based on culture) is more laborious and less precise than molecular methods in the identification of FLA (Saberi et al. 2020; Hikal and Dkhil 2018).

The subgroup analysis considering the distribution of the studies by the continents showed that FLA are more prevalent in the swimming pools and recreational water from America (63.99%), followed by Europe (51.99%) and Africa (51.27%). In relation to countries, the highest value of the prevalence of FLA was obtained in Mexico (98.35%), followed by, Malaysia (87.38%), France (69.62 %) and Italy (64.76 %), and the lowest values were obtained in China (10.15%), Taiwan (26.33%), Turkey (30.60) and Thailand (32.68%). As for the sample source, the indoor hot swimming pools presented a higher value (52.27%) of FLA prevalence, followed by public swimming pools (49.47%) and thermal swimming pools (46.05%). The genus *Vahlkampfia* spp., *Acanthamoeba* spp. and *Naegleria* spp. where more prevalent, presenting the following prevalence values, 54.20%, 33.47% and 30.95%, respectively (Table 3). The lowest prevalence value was for *Vannella* spp. (10.75%). These results are in accordance with other authors whose studies reported high prevalence of FLA (*Acanthamoeba* spp. 48.5%, *Naegleria* spp. 46.0%, *Vermamoeba* spp. 4.7% and *Balamuthia* spp. 0.7%) in hot springs (Fabros et al. 2021). Saberi et al. (2020) reported the following prevalence values for *Naegleria* spp. 44.80%, 32.88% and 21.27%, in swimming pools, hot springs and recreational waters, respectively. The subgroup analysis showed that prevalence values are statistically different (p <0.001) for all variables studied (Table 2). These findings are in accordance with other studies that reported a variable distribution in abundance and diversity of FLA species around the world (Jahangéer et al. 2020; Saberi et al. 2020; Fabros et al. 2021).

The global prevalence of FLA reported in the present study (44.34%) is worrying, since direct contact between humans and these waters is often established. In addition, several studies have reported the isolation of several potentially pathogenic FLA (Caumo et al. 2009; Alves et al. 2012; Behniafar et al. 2015;) and others with proven pathogenicity in *ex-vivo* and *in-vivo* trials (Brown and Cursons 1977; Janitschke et al. 1980; Rivera et al. 1983; Rivera et al. 1993; Gianinazzi et al. 2009). Most of these FLA are identified as *N. fowleri*, *Acanthamoeba* spp. and *Balamuthia mandrillaris*. Most isolates of *Acanthamoeba* spp. reported as pathogens are distributed among the T5, T11, T15, T3 and T4 genotypes, and among them, the T4 genotype is more prevalent in hot springs (Mahmoudi et al. 2015; Fabros et al. 2021) and is associated with most cases of *Acanthamoeba* keratitis (Diehl et al. 2021; Bellini et al. 2022). The presence and abundance of FLA in swimming pool water clearly indicates that in addition to these microorganisms being resistant to chlorine in the dosage used in the treatment of drinking water (Thomas et al. 2004; Majid et al. 2017; Gomes et al. 2020) they are also resistant to chlorine, and other disinfectants in the dosage used for swimming pools and artificial recreational waters (Rivera et al. 1983; Kiss et al. 2014; Zeybek et al. 2017). *Acanthamoeba castellanii* trophozoites and cysts have been reported to be resistant to exposure for more than 2 h to NaOCl and NaCl at concentrations up to 8 mg/L and 40 g/L, respectively. On the other hand, exposure to the combined effect of NaOCl or NaCl with ultraviolet C (UV-C) radiation resulted in rapid inactivation of trophozoites even when lower concentrations of NaOCl and NaCl were used (Chaúque and Rott 2021). Cyst inactivation was achieved by twice as long exposure (300 min) to the combined effect of NaOCl or NaCl and UV-C, with redosing of NaOCl. Despite having demonstrated that both methods are effective, and that they have a strong potential to be used in the effective disinfection of swimming pool water, it was found that the use of NaCl is more cost-effective, as it is cheaper, has a residual effect, redosing is not necessary and is simple to apply (Chaúque and Rott 2021). On the other hand, the use of solar UV radiation (UV-A and B) in place of UV-C (which depends on electricity) can further reduce the cost of the disinfection process. The effectiveness of using solar UV to photolyse NaOCl to inactivate chlorine-resistant microorganisms has been previously documented (Zhou et al. 2014). Readers interested in solar water disinfection technology applicable to recreational water treatment are directed to the appropriate literature (Chaúque and Rott 2021a; Chaúque et al. 2022).

The main aspects that constituted limitations for the present study are: the lack of studies carried out in most countries of the world; the heterogeneous distribution of the number of studies among the included countries; difference in FLA identification methods among many studies and discrepancy in the number of samples considered positive by the morphological and molecular method in the same study. The loss of isolates from positive samples in some studies, due to fungal contamination of non-nutrient agar plates prior to molecular identification of the amoebae, was also a limitation.

CONCLUSION

It is concluded that the prevalence of FLA in swimming pools and recreational waters is high and, therefore, of concern, since there is a risk of contracting infection by pathogenic amoebae or other pathogens (such as fungi, bacteria and viruses) that may be harbored and dispersed by FLA in water (Mavridou et al. 2018). Thus, it is necessary to implement disinfection techniques that are effective in eliminating microorganisms, including FLA, in swimming pools and artificial recreational waters. The use of the combined effect of NaCl and UV-C has great potential to be used to eliminate or minimize the risk of infection by FLA in swimming pools and other artificial recreational waters. The potential risk of infection by FLA in natural recreational waters needs to be routinely quantified by health surveillance. Warning signs need to be placed where there is minimal risk of infection by FLA, and people using these water bodies need to be educated about the potential risk and possible safety measures. These measures include not diving in recreational waters wearing contact lenses, preventing water from entering the airways and eyes, and avoiding jumping into the water. Health care workers (especially those working near recreational water use sites with risk of infection by FLA) need to be trained to be on the lookout for symptoms suggestive of infection by FLA, especially in summer.

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Conflicts of interest

The authors have no competing interests to declare that are relevant to the content of this article.

Availability of data and material

Not applicable

Authors' contributions

B.J.M.C. conceived the idea, wrote the project, collected and analyzed the data and wrote the manuscript. D.S. participated in the conception of the idea, performed the data verification, wrote and revised the manuscript. D.A. performed data analysis and manuscript review. M.B.R. managed the project and reviewed the manuscript. All authors approved the publication of this version of the manuscript.

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CAPÍTULO II

Artigo intitulado “The Role of Free-Living Amoebae in the Persistence of Viruses in the Era of Severe Acute Respiratory Syndrome 2, Should We be Concerned?” publicado na revista Journal of the Brazilian Society of Tropical Medicine. https://doi.org/10.1590/0037-8682-0045-2022.

The role of free-living amoebae in the persistence of viruses in the era of Sars-Cov-2, should we be concerned?

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Dear Editor

Since the beginning of the Covid-19 pandemic, humanity has accumulated unprecedented devastating consequences. Likewise, an outstanding effort was directed to combat the virus while better understanding its biology, pathogenicity, and dynamics. Despite efforts to end the pandemic, we may have to live with Sars-Cov-2 for a long time. Although the persistence of Sars-Cov in vertebrate hosts, including bats and pangolins, is increasingly clear, the role of free-living amoebae (FLA) in environmental persistence, dispersal, and perhaps the emergence of new variants need attention. The present letter aims to shed light on the role of FLA in the environmental persistence of viruses, including Sars-Cov-2, and the possible impacts that may arise from this.

FLA are protozoa that normally live and feed freely in the environment. They are cosmopolitan and ubiquitous and isolated from virtually all-natural environmental matrices, including plants, soil, and water. FLA have also been isolated from many of anthropogenic environments, for example, water from a variety of water sources, such as a well, drinking water treatment and distribution system, pool, and sewage[1,2]. FLA isolation was also performed from various surfaces in the hospital environment, including air conditioning dust. Some FLA can be opportunistic or pathogenic and can cause skin infections (mainly in immunocompromised people), keratitis, and granulomatous amoebic encephalitis (also in immunocompetent ones).

On the other hand, it has been reported that the genome of Sars-Cov-2 and viable and infectious viral particles of Sars-Cov-2, are present in the stools of symptomatic or asymptomatic infected persons, including persons with negative results for nasopharyngeal swab tests[3]. Sars-Cov-2 has also been detected in different body fluids, including urine from infected people. Consequently, Sars-Cov-2 was also found in sewage and in different bodies of fresh water such as rivers that receive sewage and groundwater reservoirs[4].

In the environment, the FLA feed on particulate organic material or prey on various microorganisms, such as protozoa, fungi, bacteria, and viruses. Some of these microorganisms escape the intracellular digestion route, surviving and multiplying within the FLA (and in many cases, they leave and recolonize the extra-amoebic environment), which is why they are called amoeba-resistant microorganisms (ARM)[5]. ARM are phylogenetically diverse and cover the main taxa with microbial representatives, including bacteria, fungi, and viruses.

Many viruses have been described as ARM, including Faustovirus, Lausannevirus, Mimivirus, Pandoravirus, Pithovirus, Yaravirus, Coxsackievirus, Adenovirus, and Human Norovirus Surrogates[6,7]. Within the FLA, viruses not only harbor and multiply but can modulate the internal environment of the amoebic host, affecting both its replication and its spread to new hosts, as shown by Mimivirus, Marseillevirus, Tupanvirus, and Faustovirus[7]. In addition, the FLA becomes a field of interactions between the different microorganisms it hosts, making amoebae a melting pot of genetic exchange where gene recombination is frequent[7]. The presence of ARM within the amoeba or the interaction of FLA with ARM can result in the acquisition, expression, or repression of virulence by FLA or ARM. The vast majority of microorganisms that express the ability to become ARM are pathogenic or opportunistic, including for humans, for example, Mimivirus, Respiratory syncytial virus (RSV), Enterovirus, and Norovirus[6-8].

Within the FLA, ARM are protected from environmental aggressions, including the biocidal properties of disinfectants, for example, human adenovirus type 5 (HAdV 5) internalized in *Acanthamoeba polyphaga* proved to be resistant to chemical disinfectants, including high doses of sodium hypochlorite (5 mg/L)[9]. Likewise, noroviruses internalized by *Vermamoeba vermiformis*, *Acanthamoeba polyphaga*, and *Willaertia magna* remained stable and infectious even after being exposed to sufficiently lethal doses of UVC radiation[10]. Furthermore, FLA allow the persistence of ARM even when environmental conditions are considerably inhospitable since amoebae trophozoites turn in cyst form when conditions become unfavorable. Cysts are structures of resistance of the FLA, with double walls consisting essentially of cellulose and proteins. They are highly resistant to a multitude of unfavorable conditions, including extremely acidic medium (pH 2), thermal shock, freezing, long-term desiccation (> 20 years), chlorine, as well as UV and gamma radiation. Viruses have been reported to remain viable in cysts, and infectious viral particles can be recovered from excised trophozoites[11].

Recently, it has been demonstrated that infectious viral particles of the Sars-Cov-2 surrogate (Phi6 phage) can be recovered from infected free-living amoebae (*Vermamoeba vermiformis*), including from infected cysts stored for up to 20 days[12].

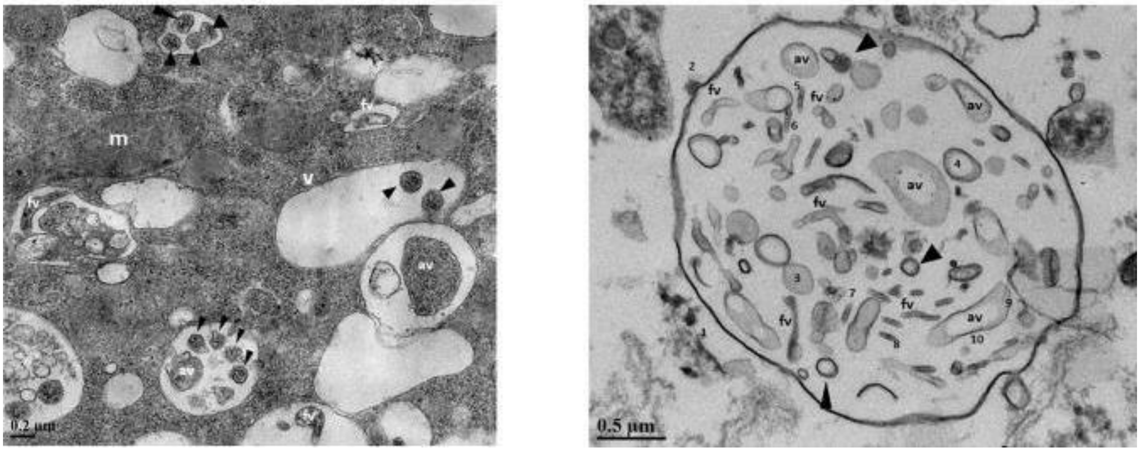

Figure 1. Transmission electron microscopy images showing respiratory syncytial virus (RSV) particles within *Willaertia magna* food vacuoles (left) and extracellular vesicles filled with polymorphic RSV virions (right). (m) mitochondria. (v) vacuoles. (black arrowheads) spherical virions. (av) asymmetric virions. (fv) filamentous virions[8], with permission: http://creativecommons.org/licenses/by/4.0/.

Taking into account the previous discussion and highlighting the fact that the FLA are ubiquitous in anthropogenic and natural environmental matrices, and are highly abundant in sewage, combined with the presence of Sars-Cov-2 in sewage and other contaminated water sources, it is probable that the chances of interaction of these two microorganisms in the environment are high. It is important to note that high titers (10^6 - 10^{11}) of Sars-Cov-2 have been reported in human excrement. Although Sars-Cov-2 is considered sensitive to sewage conditions, a relatively long time (4.3 - 6 days) maintaining infectivity in this medium has been reported[1,2]. In addition, to FLA live and be abundant in the sewer, a relatively short times (on hour) of interaction between FLA and viruses have been reported to be sufficient to internalize a considerable number of viral particles (~4×10^2), as shown for, of human noroviruses (HuNoVs) surrogates (*Murine norovirus* type 1 and *Feline calicivirus*)[11]. The FLA usually disperses internalized viruses by releasing respirable-sized vesicles (2-3 µm) filled with viral particles (Figure 1), as shown for RSV and Coxsackievirus B5[12]. This fact may increase the resistance, viability time, and range of dispersion of Sars-Cov-2 in the environment, since the vesicles will provide protection against biocidal factors until reaching a new host or less unfavorable environments[8,12]. The public health concern raised by this possibility is much more significant for rural areas of developing countries where sanitation is critical and people's exposure to contaminated water is greater. Furthermore, the interaction of Sars-Cov-2 with other ARM in the intracellular environment of FLA may favor gene recombination, which can result in the regressive or progressive evolution of the virus.

It has been speculated that FLA could serve as a model for studying the pathogenesis of Sars-Cov-2. This speculation was based on the characteristics of *Acanthamoeba* (e.g., mechanisms of molecular motility, biochemical physiology, phagocytosis, and interactions with pathogens) that have notable parallels with macrophages. Furthermore, it has been reported that *Naegleria fowleri* can express primitive forms of the ACE2 and TMPRSS2 proteins, similarly, *Acanthamoeba* spp. and *N. fowleri* can code for furin, which are proteins that have been reported as binding sites for Sars-Cov-2 to human cells.

Results of studies that aim to evaluate the *in situ* and *in vitro* interaction of Sars-Cov-2 and FLA are desirable and of great value to support the fight against the ongoing pandemic as well as future ones.

Conflict of interest

The authors declare that there is no conflict of interest.

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CAPÍTULO III

Artigo intitulado “Solar disinfection (SODIS) technologies as alternative for large-scale public drinking water supply: Advances and challenges” publicado na revista Chemosphere. https://doi.org/10.1016/j.chemosphere.2021.130754.

Solar disinfection (SODIS) technologies as alternative for large-scale public drinking water supply: Advances and challenges

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Highlights

- The discussed solutions make it possible to overcome the limitations of conventional SODIS.
- It is necessary to develop high-performance continuous flow systems for large-scale water supply
- System that combines SODIS, SOPAS and nanomaterials performs better than single approach systems.
- Protozoan cysts and bacterial spores are best targets for testing new generation SODIS systems.

ABSTRACT

Gastrointestinal waterborne diseases, continue to stand out among the most lethal diseases in developing countries, because of consuming contaminated water taken from unsafe sources. Advances made in recent decades in methods of solar water disinfection (SODIS) have shown that SODIS is an effective and inexpensive method of providing drinking water, capable of substantially reducing the prevalence and mortality of waterborne diseases. The increased impact of SODIS in communities lacking drinking water services depends on a successful upgrade from conventional SODIS (based on PET bottle reactors) in high flow continuous flow systems for solar water disinfection (CFSSWD). This review aimed to identify the main limitations of conventional SODIS that hinder its application as a large-scale drinking water supply strategy, and to propose ways to overcome these limitations (without making it economically inaccessible) based on the current frontier of advances technological.

It was found that the successful development of the CFSSWD depends on overcoming the current limitations of conventional SODIS and the development of systems whose configurations allow combining the properties of solar pasteurization (SOPAS) and SODIS. Different improvements need to be made to the main components of the CFSSWD, such as increasing the performance of solar radiation collectors, photo and thermal reactors and heat exchangers. The integration of disinfection technologies based on photocatalytic and photothermal nanomaterials also needs to be achieved. The performance evaluation of the CFSSWD should be made considering resistant microorganisms, such as the environmental resistance structures of bacteria or protozoa (spores or (oo)cysts) as targets of disinfection approaches.

Keywords: SODIS, SOPAS, Continuous-flow systems, large-scale water supply, photothermal and photocatalytic nanomaterials, resistant microorganisms.

1. Introduction

Water is a primary and determining resource for the existence of any known form of life, including humans. Accessibility and water quality stand out among the quality of life qualifiers in human settlements. Although significant progress has been made in recent decades in increasing the share of the population with access to managed and safe drinking water systems, about 2 billion people worldwide still consume contaminated water. Consequently, about 40,000 deaths are reported monthly due to preventable diarrheal diseases in low- and middle-income countries (WHO, 2019). Low-income countries in Africa and Southeast Asia are responsible for the majority of these deaths. Although about 74% of the world's population has access to safe drinking water, in Africa this rate drops to 43% (Bain et al., 2014; WHO, 2019; Nowicki et al., 2019; Chu et al., 2019). Ensuring access to safe and pathogen-free water is a fundamental and urgent issue that is why it fits into the Millennium Development Goals and Sustainable Development (WHO, 2019).

Climatic adversities combined with demographic growth, the increase in the density of urban centers and industrial growth, increase the pressure on limited water resources and on drinking water supply systems (Montgomery and Elimelech, 2007; Shannon et al., 2008; Chu et al., 2019). This fact favors that financial resources for drinking water are invested preferentially in large urban centers. Conventional drinking water systems require greater investment and are also more suitable for more densely populated settlements, such as cities (Chu et al., 2019). However, in most low-income developing countries, for example those in the Sub-Saharan region, the highest percentage of inhabitants reside in rural areas and predominantly in sparsely populated settlements. For these regions, the operationalization of the millennium goal in relation to universal access to drinking water needs to take into account unconventional water treatment approaches (Chu et al., 2019).

Solar water disinfection (SODIS) is an inexpensive method widely proven to be effective in inactivating waterborne pathogens belonging to all realms of sanitary interest, including chlorine-resistant microorganisms, for example, *Cryptosporidium* spp. oocysts, *Acanthamoeba* spp. cysts and *Bacillus subtilis* spores (Heaselgrave and Kilvington, 2011; Heaselgrave and Kilvington, 2012; Pichel et al., 2019; Chu et al., 2019). The adoption of SODIS by communities has been implicated in strengthening immunity and reducing the prevalence of diarrhea in children under 5 years of age by up to 50% (Graf et al., 2010; Ssemakalu et al., 2014; Clasen et al., 2015).

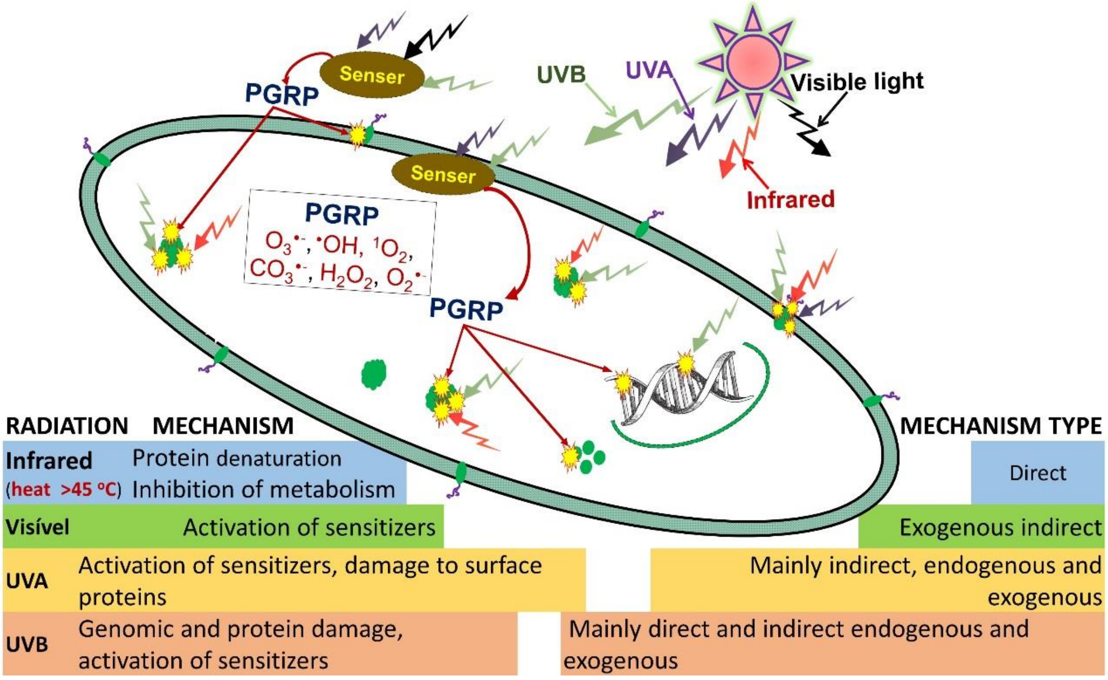
SODIS has also been widely demonstrated to be able to enhance the antimicrobial effectiveness of chlorine and to inactivate or degrade many chemical contaminants in water (Remucal and Manley, 2016; Patel et al., 2019). In addition, SODIS is an accessible method, since it does not require the use of chemical disinfectants and uses thermal and optical energy from the sun to inactivate microorganisms present in the water. However, despite this, the application of conventional SODIS as a strategy to provide drinking water to communities without access to safe-managed drinking water systems is limited, due to the inability to treat large volumes of water per day. Conventional SODIS consists of placing contaminated water in a transparent bottle, commonly made of polyethylene terephthalate (PET) and exposing it to the sun for at least 6 hours, or for up to 12 hours if the sky has about 50% cloud cover (McGuigan et al., 2012; Asiimwe et al., 2013). To overcome this limitation and allow the large-scale use of SODIS, a wide range of scientific research has been carried out and extensively reviewed on several fronts on the use of solar energy for the treatment of water for drinking purposes, in the last decades. (McGuigan et al., 2012; Classen et al., 2015; Pichel et al., 2019; Chu et al., 2019). However, it is understood that the most *impactful* advances were achieved when continuous flow systems for solar water disinfection at different scales began to be designed, built and tested (Gill and Price, 2010; Carielo et al., 2016*;* Domingos et al., 2019). These systems essentially aim to maintain or improve the efficiency of SODIS, reducing the necessary period of exposure of water to the minimum possible time, to allow large volumes of water to be processed during the day. The optimization of the configuration of continuous flow systems for solar water disinfection, improving its efficiency and maintaining accessibility, is a decisive challenge and a final step for the application of SODIS as a robust alternative for *l*arge-scale public drinking water supply, in rural and suburban contexts.

This review aimed to identify the main limitations of conventional SODIS for application as an alternative to large-scale drinking water supply, and to seek possible solutions based on available technology. It also aimed to identify the challenges that need to be overcome to allow an upgrade of conventional SODIS in continuous-flow systems for solar water disinfection (CFSSWD) with high performance, capable of providing large volumes of safe drinking water per unit of time. A discussion on the possibilities of integrating SODIS, solar pasteurization (SOPAS) and photocatalytic and photothermal nanomaterials is also presented, as a path to a new generation of high performance solar disinfection systems.

The search for the optimized integration of these different approaches to solar water disinfection is justified by the fact that they enable disinfection by the synergistic effect of heat, ultraviolet radiation and photo-generated reactive products (PGRP) (Wang et al., 2015; Castro-Alférez et al., 2016; Alférez et al., 2017; Nelson et al., 2018). The disinfection process using integrated solar disinfection systems will allow microbial contaminants to be instantly targeted by different biocidal factors, resulting in serious irreversible cell damage. This would result in rapid microbial inactivation during a rapid passage of water through the system.

The modeling and mechanisms of solar photoinactivation of bacteria and viruses in the water matrix, by means of visible and UV radiation, have been extensively revised (Nelson et al., 2018). The inactivation of microorganisms by solar energy occurs essentially in three ways: direct mechanism as well as by the indirect endogenous or indirect exogenous mechanism (Fig. 1) (Nelson et al., 2018).

The direct mechanism occurs when the solar energy (photon or heat) is absorbed by the photosensitive structures / chromophores (such as genome, proteins or other biomolecules) located inside the microorganism, compromising its chemical structure and function. The indirect mechanism is that which occurs when endogenous (located within the microorganism) or exogenous (located within the microorganism) photosensitive structures absorb energy, triggering the generation of PGRP that cause damage to different structures of the microorganism (Fig. 1) (Castro-Alférez et al., 2016; *Castro-Alférez et al., 2017;* Nelson et al. , 2018).



RADIATION	MECHANISM	MECHANISM TYPE
Infrared (heat >45 ºC)	Protein denaturation Inhibition of metabolism	Direct
Visível	Activation of sensitizers	Exogenous indirect
UVA	Activation of sensitizers, damage to surface proteins	Mainly indirect, endogenous and exogenous
UVB	Genomic and protein damage, activation of sensitizers	Mainly direct and indirect endogenous and exogenous

Figure 1: Schematic representation of the mechanisms of synergistic inactivation of microorganisms by solar energy. In direct mechanisms, energy damages the biomolecule absorption site (yellow light). In indirect mechanisms, energy is absorbed by a sensitizer and induces the generation of PRF that damage the biomolecule site (yellow light) that has not absorbed energy. Proteins are represented in green. PGRF – Photo-generated reactive products.

2. Solar disinfection, effectiveness and impact

Ensuring access to drinking water for the population remains a challenge in the world (WHO, 2019). The majority of people without access to safe managed drinking water systems, capable of providing water whose consumption does not pose a significant health risk, reside in low-income developing countries, such as those in sub-Saharan Africa, Latin America and the West Asia (Bain et al., 2014). This has resulted in a high prevalence of waterborne diseases and loss of human life, especially for children. In addition, these regions without access to drinking water tend to have higher peaks in cases of malnutrition, especially among children (Bain et al., 2014; WHO, 2019). The search for solutions to this problem needs to consider unconventional drinking water management strategies, such as treatment at the point of use, including solar disinfection technologies that best suit rural and suburban contexts (Chu et al., 2019). The effectiveness of solar water disinfection has undoubtedly been demonstrated and widely reviewed for a wide range of microorganisms, including bacteria, viruses, phages, fungi, as well as protozoa (McGuigan et al., 2012; Heaselgrave and Kilvington, 2012; Pichel et al., 2019). It was established that in the conventional SODIS process based essentially on the synergy of the optical and thermal effect of solar radiation, the acceleration of microbial inactivation occurs in proportion to the increase in water temperature, especially from 30 ºC to 45 ºC (Rijal and Fujioka, 2001; Berney et al., 2006; Castro-Alférez et al., 2017; Vivar et al., 2017; Nwankwo et al., 2019). Heat (infrared 760 – 1400 nm) induces the denaturation of structural proteins (e.g.,, cytoskeleton), as well as functional proteins (e.g., enzymes) that compromise the physical and metabolic integrity of microorganisms (Castro-Alférez et al., 2017; Vivar et al., 2017). UV radiation, predominantly UVB (280-320 nm), triggers direct damage to different chromophores (e.g., genome, proteins, NADH, porphyrins) compromising its chemical structure and thereby its function. Although UVA (320-400 nm) is also implicated in direct cell damage, it is predominantly responsible for the indirect mechanisms of cell damage by sensitizing sensitizers (e.g., nitrate, nitrite, photocatalytic metal complexes) for the production of PGRP (e.g., $O_3^{\bullet -}$, $^{\bullet}OH$, $^1O_2$, $CO_3^{\bullet -}$, H_2O_2, $O_2^{\bullet -}$) which, in turn, damage the various microbial components. Solar radiation in the visible spectrum (400 - 700 nm), as well as UVB, is also involved in indirect damage (Fig. 1) (Wang et al., 2015; Nelson et al., 2018). Readers interested in details about the microbial photoinactivation mechanism should consult the appropriate literature (Nelson et al., 2018).

Several teams of researchers have already reported the impact of using SODIS as a water treatment strategy on improving the health of communities. For example, a decrease of about a quarter to a third in the prevalence of diarrhea has been reported in children under 5 years of age, in communities that have received training in SODIS and PET bottles with instructions on how to proceed. In families that directly adopted SODIS, they showed a 50% reduction in prevalence (Graf et al., 2010; Clasen et al., 2015). These improvements were seen in communities that had access and those that did not have access to improved sources of drinking water (Clasen et al., 2015). In another community, SODIS has been implicated in reducing the risk of waterborne diseases by 90 to 96% (Islam et al., 2015). It has been strongly suggested that the improvement in the health status of populations that consume treated water through SODIS, mainly in developing countries, is attributed to the consumption of water free from viable microorganisms. But is also attributed to the immune status of resilience, induced by the consumption of inactivated pathogens present in the treated water (Ssemakalu et al., 2014; Ssemakalu et al., 2015). It has been suggested that the peak of immunization against waterborne diseases, such as cholera, occurs mainly during outbreaks, when treated water is loaded with sufficiently high doses of antigens to induce the development of specific antibodies (Faria and Weiner, 2005; Ssemakalu et al., 2014). *Vibrio cholerae* cells inactivated through SODIS have been shown to be able to induce the secretion of pro-inflammatory cytokines and chemokines by dendritic cells. (Ssemakalu et al., 2015).

3. SODIS limitations and ways to overcome them

Conventional solar disinfection, which consists of exposing a large amount of water contained in plastic bottles (predominantly PET) to the sun, is widely demonstrated to be an effective and cost-effective technique (McGuigan et al., 2012; Piche et al., 2019). Despite this, certain limitations make it difficult to maximize the use of its potential, so it cannot yet be used as an alternative strategy for large-scale public water supply. The main limitations of SODIS as well as ways to overcome them are presented and discussed in the following paragraphs.

3.1. Low volume of treated water and possible genotoxicity of PET reactors

One of the main limitations of SODIS is the small volume of water that can be processed per day, which is usually less than 3 liters per batch, which corresponds to the size of PET bottles. Although PET bottles are considered suitable for SODIS (because they have a cost-benefit advantage) and their correct use does not represent a significant toxicological and genotoxic risk

(Wegelin et al., 2001, Schmid et al., 2008), they are less abundant in rural areas, where SODIS is most needed. This fact is aggravated by the fact that regular replacement of plastic bottles is necessary, as it is strongly recommended that successive prolonged reuse (for more than 6 months) is avoided (Ubomba-Jaswa et al., 2010). Furthermore, long-term storage of disinfected water is not recommended, although bacterial growth is not observed after the water reaches complete disinfection when kept indoors for up to a week, at a temperature below 30 ºC (Vivar and Fuentes, 2016). Greater care should be taken to avoid post-treatment contamination, and for that the water would need to be kept in the same bottle to limit the possibilities of contamination, but this would not be practicable given the low abundance of PET reactors in rural areas. In addition, the genotoxicity of water kept in a PET bottle for at least one month has been reported due to the migration of plastic derivatives, even in bottles kept in the dark (Ubomba-Jaswa et al., 2010). The need to establish a daily routine to fill bottles and expose them to the sun can overload daily activities and, therefore, constitute a limitation to the continuous availability of treated water.

These limitations can be overcome with the use of glass bottles or other materials that have greater optical stability and that have a transmittance rate equal to or greater than that of the PET bottle for the UV spectrum. Reactors made of materials such as polypropylene, polymethylmethacrylate, pyrex (with low iron content), borosilicate methacrylate and quartz are more promising (McLoughlin et al. 2004; Gill e Price, 2010; Ayoub and Malaeb, 2019; García-Gil et al., 2020). However, prices for reactors made of most of these materials would be impractical for rural contexts, especially in low-income countries, where SODIS is most needed.

Another alternative solution to increase the volume of water treated per batch would be the construction of PET reactors with a larger volume. However, in this case it would be necessary to take care to optimize, the wall thickness and the width of the reactor, in order to allow the thickness of the water body to be thin enough to allow the radiation that passes through the reactor wall, to reach the bottom of the reactor, in order to guarantee the desired efficiency. In this case, plastic PET bags would be more suitable, because in addition to being effective, they are easier to transport, since a considerably high number of units can be transported in a relatively smaller space (Lawrie et al., 2015; McGuigan et al., 2012). These reactors are especially suitable for emergencies, such as environmental or humanitarian disasters, where drinking water for consumption is not available. Despite this, access to these reactors will be a limiting factor, as they will be relatively more expensive, as they should be produced exclusively for this purpose. In addition, although these reactors allow an increase in the amount of water treated per batch, this does not solve the problem of a lower volume of disinfected water per day through SODIS, since the proportion of disinfected water as a function of the irradiated area of the reactor remains the same.

- Ways to overcome low volume water and potential PET genotoxicity

Before discussing the improvements needed to increase the volume of water treated per day through SODIS, it is important to say that the term "SODIS" in the literature is tacitly used as a disinfection technique based on the use of the sun's optical (UV) properties for inactivate microorganisms. This understanding is favored by the need to distinguish SODIS from SOPAS (solar pasteurization). Although both are disinfection techniques based on the use of solar radiation, SOPAS is a generic name for all technologies that use thermal radiation from the sun (infrared radiation) to inactivate microorganisms present in liquids, such as water. However, essentially SODIS is based on the optical and thermal synergy of the sun to inactivate microorganisms, because in practice this does not occur and it is not desirable to separate the thermal and spectral components during SODIS, as it is not advantageous (Vivar et al., 2017; Nwankwo et al., 2019). It is safe to say that temperatures above the optimum temperature for microbial growth associated with UV have a certain level of synergy in the inactivation of microorganisms during SODIS, and the strength of this synergy depends on the intensity of heat and UV, as well as the time of exposure and the susceptibility of the target microorganism (Giannakis et al., 2014). In general, a strong synergy occurs from temperatures above 40 ºC (Giannakis et al., 2014; Vivar et al., 2017; García-Gil et al., 2020). On the other hand, temperatures around the optimum temperature for microbial growth have an antagonistic effect to the SODIS process (Giannakis et al., 2014; Vivar et al., 2017).

Overcoming the limitation of the low volume of water that can be disinfected daily through SODIS, it will only be possible if it is possible for the water temperature to rise rapidly until reaching high synergy temperatures, and ensure that the water receives high doses of solar UV radiation for a short exposure time. The synergy between thermal and spectral radiation must be strong enough to ensure that complete inactivation of microorganisms, including resistant ones (e.g., certain viruses, bacterial spores, protozoan (oo)cysts) is achieved within the shortest possible time. Thus, the success in increasing the productivity of SODIS aiming at its application for drinking water supply on a large scale depends on the development and improvement of continuous-flow systems for solar water disinfection (CFSSWD).

Achieving these levels of advancement is only possible through the integration of different available technological advances applicable to SODIS. The necessary improvements mainly include those that allow increase the capture, concentration and conversion of solar energy into internal heat for efficient use. It is also a priority to integrate and optimize technologies to maximize the capture, concentration and effective use of solar ultraviolet radiation. The improvement of the solar collectors of the concentrator type, the increase of the heat exchange efficiency of the absorbers and the optimization of the reactors are decisive steps. The integration of technologies based on photocatalytic and photothermal nanomaterials (see more details in Section 5.8), optimizing their safety for human and environmental health, as well as their economic viability is a promising achievement to increase the daily productivity of SODIS (Chu et al., 2019; Dutta et al., 2019; Huo et al., 2020).

3.2. Resistant microorganisms

In general, bacterial pathogens, fungi and most waterborne viruses are highly sensitive to solar disinfection and easily inactivated through SODIS or solar pasteurization (SOPAS) (Berney et al., 2006; Asiimwe et al., 2013; Dunlop et al., 2011; McGuigan *et al*., 2012; Heaselgrave and Kilvington, 2012; Pichel et al., 2019). However, certain groups of microorganisms are resistant to the solar disinfection process and are generally resistant to conventional disinfection processes, including chlorination and ozonation. In addition to prions and bacterial spores (e.g., *Bacillus subtilis* spores), the forms of environmental resistance of protozoa (as *Acanthamoeba* spp., *Cryptosporidium parvum*, *Cyclospora cayetanensis*, *Entamoeba histolytica*, *Giardia intestinalis*, *Naegleria fowleri*, *Toxoplasma gondii*) stand out among microorganisms that express high resistance to chlorine and ozonation (WHO, 2006; Hijnen et al., 2006; Malato et al., 2009; Soliman et al., 2018). The microorganisms listed above are the ones that most challenge the conventional SODIS process, although the inactivation or considerable reduction in the viability of many of them has already been reported in the literature (Mendez-Hermida et al., 2005; McGuigan et al., 2006; Boyle et al., 2008; Malato et al., 2009; Heaselgrave et al., 2011; Soliman et al., 2018; Pichel et al., 2019). However, the more recalcitrant the microorganism is, the longer the exposure time to high doses of solar radiation will be required to achieve water disinfection. This leads to the understanding that the volume of water that can be processed per day through SODIS is much lower when resistant microorganisms are considered as targets, than the volume estimated by the vast majority of studies that predominantly used *Escherichia coli* and other related bacteria, as targets of conventional or enhanced SODIS and SOPAS processes (Boyle et al., 2008; Domingos et al., 2019; McGuigan et al., 2012; Pichel et al., 2019). The main microorganisms of sanitary interest associated with drinking water that express considerable resistance to SODIS, and their profile of resistance to batch disinfection processes are described (Table 1).

In certain cases, SODIS has been shown to be more effective in inactivating resistant microorganisms than conventional disinfection processes. For example, it has been reported that oocysts of *Cryptosporidium* spp. exposed to chlorine (5.25% or 4 ppm) for 120 minutes or for up to 4 days remained infectious (Fayer, 1995; Soliman et al., 2018). However, a total loss of infectivity of 4 $\log_{10}$ was obtained when the oocysts were submitted to conventional SODIS for 8 hours (Soliman et al., 2018). On the other hand, the inactivation of chlorine-resistant microorganisms improving the effectiveness of chlorine-based disinfectants, through the photolysis of the free chlorine available during SODIS, is described in the literature (Zhou et al., 2014; Remucal and Manley, 2016, Chaúque and Rott, 2021).

Table 1. Chlorine-resistant microorganisms and their rate of inactivation by batch SODIS

Species	**Treatment**	**Fluency**	**T °C**	**Time** (hours)	**Inactivation**		**Ref.**
					Log.	**%**	
Bacillus subtilis (spores)	Natural sunlight	39.95 x 10^6 W/m^2	20–40	8	0.5	96	Boyle et al., 2008
	Natural sunlight	79.9 x 10^6 W/m^2	20–40	16	1.3	96	
	Simulated sunlight	870 W/m^2 (UVB) 200W/m^2 (UVA)	40	8	1.7	28	Lonnen et al., 2005
	Simulated sunlight + TiO_2	870 W/m^2 (UVB) 200W/m^2 (UVA)	40	8	1.1	20	
Cryptosporidium parvum (oocysts)	Simulated sunlight + TiO_2	870 W/m^2 (UVB) 200 W/m^2 (UVA)	40	6	5.95	85	Mendez-Hermida et al., 2005
	Simulated sunlight	830 W/m^2	40	12	7	100	
	Natural sunlight	~56 x 10^6 W/m^2	22-32	24	~ 5.1	89	Mendez-Hermida et al., 2007
	Natural sunlight + TiO_2	~56 x 10^6 W/m^2	22-32	24	~ 5.8	100	
	Natural sunlight	1037 x 10^3 W/m^2	20-25	12	~ 6	88.4	Gomez-Couso et al., 2009
Acanthamoeba polyphaga (cysts)	Simulated sunlight	870 W/m^2 (UVB) 200W/m^2 (UVA)	40	8	0.05	1.19	Lonnen et al., 2005
	Simulated sunlight + TiO_2	870 W/m^2 (UVB) 200 W/m^2 (UVA)	40	8	0.05	1.19	
Acanthamoeba polyphaga (trophozoites)	Simulated sunlight	870 W/m^2 (UVB) 200 W/m^2 (UVA)	40	6	4.2	100	
Acanthamoeba castellanii (cysts)	Simulated sunlight	550 W/m^2	≤ 45	6	2.2	36	Heaselgrave et al., 2011
	Simulated sunlight + riboflavin	550 W/m^2	≤ 45	6	3.8	64	
Naegleria gruberi (cysts)	Simulated sunlight	550 W/m^2	≤ 45	6	3.5	60	
N. gruberi (cysts)	Simulated sunlight + riboflavin	550 W/m^2	≤ 45	6	3.8	64	
Entamoeba invadens (cysts)	Simulated sunlight	550 W/m^2	≤ 45	6	1.9	32	
	Simulated sunlight + riboflavin	550 W/m^2	≤ 45	6	1.9	31.6	
Giardia lambia (cysts)	Simulated sunlight	550 W/m^2	≤ 45	6	1.9	32.6	
	Simulated sunlight + riboflavin	550 W/m^2	≤ 45	6	1.9	32.3	
Giardia muris (cysts)	Simulated sunlight	830 W/m^2	40	4	4	100	McGuigan et al., 2006

T °C – Temperature.

3.2.1. Implication of protozoa for SODIS

The presence of protozoa in the water to be treated by SODIS is problematic, because, as well as many of them being gastrointestinal pathogens associated with the consumption of contaminated water, they are cosmopolitan and ubiquitous. In addition, they are primarily resistant to conventional accessible disinfection processes, including those based on chlorine (Schuster, 2002; Thomas et al., 2004; Thomas and Ashbolt, 2010 Thomas et al., 2010; Gomes et al., 2020). Their resistance is due to the fact that they can alternate their form of occurrence in the environment, which can occur in the form of trophozoites, during which they move, feed, reproduce and trigger pathogenicity. Or even, they occur in the form of cysts, which are their form of environmental resistance, during which the protozoan protects itself from environmental stressors, such as dissection, food shortages and extreme chemical, spectral and thermal changes in the environment. (Thomas et al., 2010). The cystic phase of the protozoan is the main determinant of the resistance expressed by the protozoan to the different water disinfection mechanisms. The cysts are made up of a thick outer wall composed of different polysaccharides that contain the vegetative form inside; the wall is a robust barrier against potential aggressors of a mechanical, chemical or physical nature (Garajová et al., 2019). When the stressor ceases (e.g., the degradation of residual chlorine) and the environmental conditions become favorable again, the vegetative form leaves the cystic envelope and returns to the trophozoic form; this alternation can occur as many times as necessary for the survival of the protozoan (Schuster, 2002; Thomas et al., 2010; Garajová et al., 2019).

One of the most impactful implications for SODIS is related to protozoa called free-living amoebae (FLA); in the environment, these amoebae live by feeding on particulate organic material and, mainly, by feeding on other microorganisms, such as bacteria, viruses, other protozoa and yeast fungi. (Thomas et al., 2010; Schuster, 2002). However, certain microorganisms escape the amoebic intracellular digestion pathway, leaving the phagosome before fusing with the lysosome, and survive in the cytoplasm and, in many cases, can multiply intensely before escaping the cell, which is why they are called amoeba-resistant microorganisms. (ARM). During the time that the ARM remain hosted in the amoeba, they can recombine their genome, through the exchange of gene fragments between the ARM or with the amoeba (Chan et al., 2018). This recombination can result in the induction of virulence factors by the host amoeba or in the acquisition and expression of virulence genes by the amoebae and ARM (Berk et al., 2008; Wang and Wu, 2017; Nakagawa, et al., 2019). It is important to note that the vast majority of microorganisms known as ARM are pathogenic; in addition, it has been estimated that about 18.9% of the approximately 539 bacteria described as pathogenic to plants or animals, including humans, are ARM (Thomas et al. 2010).

Among the FLA described as capable of hosting and dispersing microorganisms, those belonging to the genus *Acanthamoeba* stand out (Hijnen et al., 2006). It has been shown that 100% of the *Acanthamoeba castellanii* trophozoites hosted *Legionella pneumophila*, while only 2% of the *Naegleria lovaniensis* trophozoites were infected after these two protozoa were incubated in water previously contaminated by various bacterial species, including *L. pneumophila* (Declerck et al., 2005). It has been reported that after *A. castellanii* trophozoites were added to water previously contaminated by a complex community of bacteria, there was an increase in the abundance of pathogenic bacteria and an inhibition of the growth of other oxygen-consuming (non-pathogenic) bacteria, leading to recovery of dissolved oxygen concentration (Tsai et al., 2020).

The presence of FLA and its implication in the persistence of pathogenic bacteria in the treated water, as well as in the treatment plants and drinking water distribution network, is widely documented in the literature (Thomas et al., 2004; Thomas et al., 2010; Thomas and Ashbolt, 2010; Taravaud et al., 2018; Gomes et al., 2020). Today it is known that FLA are generally ubiquitous in treatment and storage systems, as well as in the drinking water distribution network, resisting conventional disinfectants, favoring the persistence, increased resistance and virulence of bacterial pathogens (Schuster, 2002; Thomas et al., 2004; Thomas and Ashbolt, 2010; Thomas et al 2010; Miller et al., 2017; Geoffrey et al., 2020; Gomes et al., 2020). When the residual effect of disinfectants ceases, the FLA favors a quick recolonization of water by the ARM, and in certain cases reaching a density similar to that, which existed before the disinfectant was administered, as shown previously for *L. pneumophila*, (Thomas et al., 2004; Declerck et al., 2005; Gomes et al., 2020). *Acanthamoeba* spp. it has also been implicated in the survival of *Legionella* at pasteurization temperatures, the bacteria remained viable after cocultures were exposed for 30 minutes at temperatures between 50 – 70 °C, and remained cultivable at temperatures between 50 - 60 °C (Dobrowsky et al., 2017).

The problem of the presence of protozoa in the water to be treated by SODIS becomes much more worrying because disinfection by solar radiation has no residual effects. Therefore, it is necessary to ensure that complete disinfection of the water is achieved by inactivating not only the pathogens associated with outbreaks, but also the FLA and its forms of environmental resistance (cysts and oocysts).

- Ways to overcome the problem of resistant microorganisms, including protozoa

The need to overcome the problem of resistant microorganisms imposes the need to readjust the targets of the processes of solar disinfection. In this case, the disinfection conditions (temperature, UV doses and exposure time) must be adequate to guarantee the complete inactivation of resistant microorganisms, such as prion viruses, bacterial spores and protozoan (oo)cysts (WHO, 2006; Malato et al., 2009; Soliman et al., 2018).

García-Gil et al. (2020) developed a predictive model for the inactivation of oocysts of *C. parvum* by SODIS, which was validated with experimental data. The data showed that the isolated effect of a temperature of 40 ºC exerts biocidal activity, and a temperature of 45 ºC can compromise the viability and infectivity > 90% of oocysts (8 x 10^4), exposed for 6 hours. However, the synergy of thermal and spectral radiation inactivates the oocysts of *C. parvum* in less time, and the exposure time required to achieve complete inactivation is inversely proportional to the temperature and UV fluency used. A strong thermo-spectral synergistic effect was reported when a temperature of 44 ºC was associated with 40 - 50 W/m^2, and complete inactivation of *C. parvum* oocysts was achieved in 3 or 4 hours, respectively. However, the data showed that the reactor's transmittance is decisive for the performance of SODIS, and

PET-based reactors are less effective than those made of polypropylene (PP) or polymethylmethacrylate (PMMA) are. While the complete inactivation of 4 $\log_{10}$ by the synergy of 44 ºC and 50 W/m^2 was achieved in about 5 and 4 hours using PP and PMMA reactors, it took 6 hours to inactivate about 3 $\log_{10}$ under the same conditions using PET reactors (García-Gil et al., 2020).

The relative inefficiency of PET reactors is because this material is impervious to UVB radiation. (McGuigan et al., 1998; Mbonimpa et al., 2012; Ayoub and Malaeb, 2019; García-Gil et al., 2020). The solar UVA associated with visible light causes the occurrence of internal damage by the formation of oxidizing radicals within the oocyst, but does not cause damage to the wall; therefore, the radicals formed externally do not increase the inactivation of the oocysts, as they will not be able to enter the oocyst, because the wall remains intact. UVB radiation, in turn, causes direct damage to the genome of the oocyst, ensuring a more effective inactivation, inducing a negative regulation of most of the genes responsible for cellular metabolism and compromising the expression of stress protection mechanisms in oocysts after 30 minutes of exposure to UVB (Liu et al., 2015).

The inclusion of disinfection technology based on photocatalytic nanomaterials to ensure the inactivation of resistant microorganisms is strongly recommended. The literature shows that photocatalytic materials considerably increase the effectiveness of SODIS (Misstear and Gill, 2012; McMahon et al., 2017; Yazdanbakhsh et al., 2019; He et al., 2021) and allow the use of the visible radiation spectrum solar (400 - 70 nm) (Chang et al., 2012; Wang et al., 2015; Birben, et al., 2016) that is not used in conventional SODIS processes.

The biocidal activity exerted by photocatalytic nanomaterials results from their sensitization by light and triggering the oxidation of water and other dissolved susceptible substances, resulting in the generation of reactive oxidants (Foster et al., 2011; Liou and Chang, 2012). These oxidants cause severe cell damage that can lead to cell death (Foster et al., 2011). The development of CFSSWD capable of using the synergy of the biocidal effects of heat, UV radiation and reactive oxidants photo-generated by photocatalytic nanomaterials will increase the certainty of the inactivation of resistant microorganisms in water.

The evaluation of the efficacy of the high flow CFSSWD to be developed, must be made to measure its capacity to inactivate these microorganisms. Likewise, the information available in the literature should be considered when defining the disinfection conditions to be implemented during water treatment.

3.3. Intermittent nature of sunlight availability

Conventional SODIS depends on the availability of solar radiation, therefore, disinfection occurs in real time when solar energy reaches the reactor, and when solar energy becomes unavailable, disinfection ceases, for this reason the intermittent nature of the availability of sunlight it is a limitation (Sansaniwal, 2019). In addition, it obviously means that SODIS does not occur at night, the availability of treated water cannot be guaranteed on very cloudy or rainy days (especially when it rains on successive days). Although it is theoretically possible to drink the water taken directly from the rain, as it is sterile or has a low rate of microbial contamination, the direct collection of sufficient volumes for consumption is a challenge or practically impossible. Normally, the roofs do the harvesting of large volumes of rainwater. Although water collected through roofs is less likely to have a high density and diversity of microorganisms at the time of collection, when compared to surface water, it is not safe for immediate consumption, so prior disinfection is necessary (Strauss et al., 2016; Chubaka et al., 2018; Reyneke et al., 2018). The presence of different pathogenic microorganisms, including, *Aeromonas* spp., *Campylobacter* spp. *Klebsiella* spp., *Legionella* spp., *Pseudomonas* spp., *Enterococcus* spp., *Salmonella* spp., *Shigella* spp., *Yersinia* spp., *Mycobacterium avium*, *Cryptosporidium* spp. and *Giardia*, have been reported in rainwater harvested through roofs (Dobrowsky et al., 2015; Chubaka et al., 2018).

- Ways to overcome intermittent availability of sunlight

The high flow CFSSWD makes it possible to provide large volumes of treated water above the daily amount needed to supply communities, so that the surplus can be temporarily kept in reservoirs and made available on cloudy and rainy days.

Water treatment plants must be designed to meet the population's daily water demand and allow adequate reserves of treated water. The tanks must allow the continuous renewal of the water, for example, the water that comes out of the disinfection system must force the exit of the water that is already in the reservoir.

3.4. Water turbidity

The turbidity of raw water plays a decisive role in achieving complete disinfection within the predominantly recommended exposure time of 6-12 hours (Kehoe et al., 2001; McGuigan et al., 2012). A level of turbidity above 30 NTU, seems to be consensually considered by the authors as being capable of compromising the effectiveness of SODIS (Gómez-Couso et al., 2009; Dawney and Pearce, 2012). This is mainly due to the fact that turbidity reduces the transmittance of water to UV radiation (Kehoe et al., 2001), so a physical treatment step to remove or reduce turbidity needs to be implemented before the water is subjected to SODIS. The fact that community members have access to raw water with different levels of turbidity, and the lack of instruments to measure the level of water turbidity, is a challenge for the success of SODIS.

- Ways to overcome water turbidity

The removal or reduction of turbidity to adequate levels (for the effectiveness of SODIS and for human consumption) in the raw water can be achieved through the inclusion of a pre-treatment step, installing slow filters also known as biosand filters (Sizirici, 2018). In addition to being accessible, biosand filters are effective in removing turbidity and improving other aspects of the physical-chemical and microbiological quality of water. They are capable of considerably removing bacteria present in water, including *E. coli, S. Typhimurium, E. faecalis* and *P. aeruginosa* (Romero et al., 2020; Medeiros et al., 2020; Andreoli and Sabogal-Paz, 2020). Although biosand filters are no better than other methods of removing turbidity in water (for example, coagulation-flocculation, membrane filtration, etc.), they have some peculiar advantages, such as accessibility, they are environmentally friendly, their use and maintenance does not require specialized labor and materials for its construction are available anywhere these filters are needed. The filtered water can be stored in a raw water tank before being subjected to the disinfection step.

3.5. Social barriers

The impact of SODIS on the prevalence of waterborne diseases in a region is strongly conditioned by the belief of a significant portion of the population about the effectiveness of this technique in providing safe water for consumption (Bitew et al., 2020). This belief must necessarily result in the acceptance, adoption and continued use of SODIS by the population, and this practice should be replicated by other members of the community, to counterbalance the number of people who eventually abandon SODIS and return to old habits. The fact that the total volume of drinking water provided by SODIS in a community, is dependent on the daily behavior of the members of each family, is a limitation to the success of SODIS in the medium and long term.

- Ways to overcome social barriers

The installation of solar water treatment stations, based on CFSSWD in the communities, will allow the overcoming of several socio-cultural limitations identified as barriers to the success of SODIS. The availability of drinking water will not be conditioned by individual social beliefs, availability of PET bottles, and low knowledge about SODIS or the self-discipline of each family to carry out SODIS procedures correctly. However, the success of water treatment and distribution plants (especially in rural contexts in developing countries) depends on observing some precautions, from choosing the installation site to maintenance (Mahon and Gill, 2018).

A study by Gill and Price (2010) in a Kenyan village, shed some light on this reality. These authors installed a continuous-flow solar water disinfection system (Fig. 4 A) (details are presented in section 6.2). Three years after installation, it was found that climatic variables (for example, droughts and floods) associated with cultural, infrastructural, financial and technical factors compromised the use and performance of the system in the short and long term (Mahon and Gill, 2018). Experience has shown that for the successful implementation of SODIS systems in rural contexts in developing countries, the participation of the benefited community is indispensable. That is why it is essential to ensure the involvement of local partners, including Universities, and to consider alternative sources of funding, to allow the continuity of effective monitoring and evaluation in the medium and long term. (Gill and Price, 2010; Mahon and Gill, 2018).

It is necessary to apply transdisciplinary strategies with the objective of involving local communities to ensure the successful implementation of water treatment and supply stations (Morse et al., 2020), taking into account all factors that may become barriers to the implementation of the CFSSWD (Morse et al., 2020; Bitew et al., 2020).

4. Current stage and possibilities for the development of CFSSWD for large-scale water supply

Since SODIS has been demonstrated as an effective and affordable technology for microbial water treatment, which can be applied to provide drinking water to communities without access to drinking water, efforts have been made to increase the volume of water that can be disinfected daily (Duff and Hodgson, 2005; Ubomba-Jaswa et al., 2010a; Polo-López et al., 2011; Chaudhari et al., 2013). These efforts resulted in the development of some CFSSWD, of the type SODIS, SOPAS or mixed (e.g. Carielo et al., 2017; Monteagudo et al., 2017; Sizirici, 2018; Domingos et al., 2019).

4.1. SOPAS-type continuous-flow systems

Duff and Hodgson (2005) developed and tested a solar pasteurization system with a convection circuit, which works based on the density of the water. The system consisted of a heat collector composed of five evacuated tubes with a total absorption area of 0.45 m^2, connected to a collector tube. A U-shaped tube was placed before the collector tube to ensure that the water circulates in a clockwise direction (Fig. 2 A). As the water temperature rises in the collector tube and becomes less dense than the cold water that come from the storage tank, it circulates through the riser pipe and returns to the collection tube through the convection tube. This allows the circulating water to have almost the same temperature (in the collecting, ascending and convection tubes). When the circulating water reaches the appropriate temperature (~ 78 ºC), it overflows into the holding tube, flowing to the treated water tank through the heat exchanger where it preheats the water that leaves the raw water tank. The system reached a maximum production of 19.3 L/h, when the incident solar radiation was about 955 W/m^2.

Manfrida et al. (2017) also submitted the design of the system designed by Duff and Hodgson (2005) to a performance evaluation. An explanation of the circuit sizing and a time-dependent off-design model was presented to examine the daily and seasonal productivity of the project in different contexts. A compensation tank was added to the project to contribute to the establishment of a thermal inertia that has a positive effect in the case of transient reductions in the incidence of radiation, due to the temporary shading by clouds (Fig. 2 B).

The study included an exergetic analysis, the definition and evaluation of performance indicators, as well as the simulation for different locations.

It has been reported that destruction of exergy and losses in the solar collector are prevalent, and that the system is strongly influenced by local environmental conditions, such as latitude and temperature. The system's productivity varies in different months of the year for different countries, with higher expected productivity in months with higher solar irradiation values.

Simulations demonstrated that the system is capable of producing 40 to 80 L of pasteurized water per collecting surface daily, depending on the location.

Bigoni et al. (2014) built and tested an intermittent flow solar pasteurizer based on a parabolic cylindrical concentrator solar collector, measuring 3 meters in length and 1.9 m in width. The mirrors were made of polished aluminum sheets, and the black painted steel tubular absorber was placed in the center of the luminous chiasma formed by reflected solar radiation (focus).

The end of the absorber was equipped with a thermostatic valve, adjusted to open at 87 ºC and close between 82 – 83 ºC (Fig. 2 C). The opening of the valve occurred between 30 to 60 minutes depending on climatic conditions.

Complete disinfection of the river water was achieved, which contained 2–9x10^9 CFU/100mL of *E. coli,* and a daily production of 66 L of pasteurized water was reported. However, samples incubated for up to 72 hours showed bacterial growth (Bigoni et al., 2014).

Dobrowsky et al. (2015) tested an Apollo™ solar heater (from Apollo Solar Power Company) to disinfect contaminated rainwater harvested from the roof (Fig. 2 D). The collector consists of evacuated borosilicate tubes painted in black, and they absorb the heat from direct solar radiation, occupying a total collection area of 0.96 m^2. The tubes are successively connected to each other, and the tubes inlet and outlet connect to the pasteurization tank. The cold (denser) water in the pasteurization tank pushes hot water (less dense) into the tubes, causing it to rise into the pasteurization tank. The continuous circulation of water causes the water in the pasteurization tank to heat up.

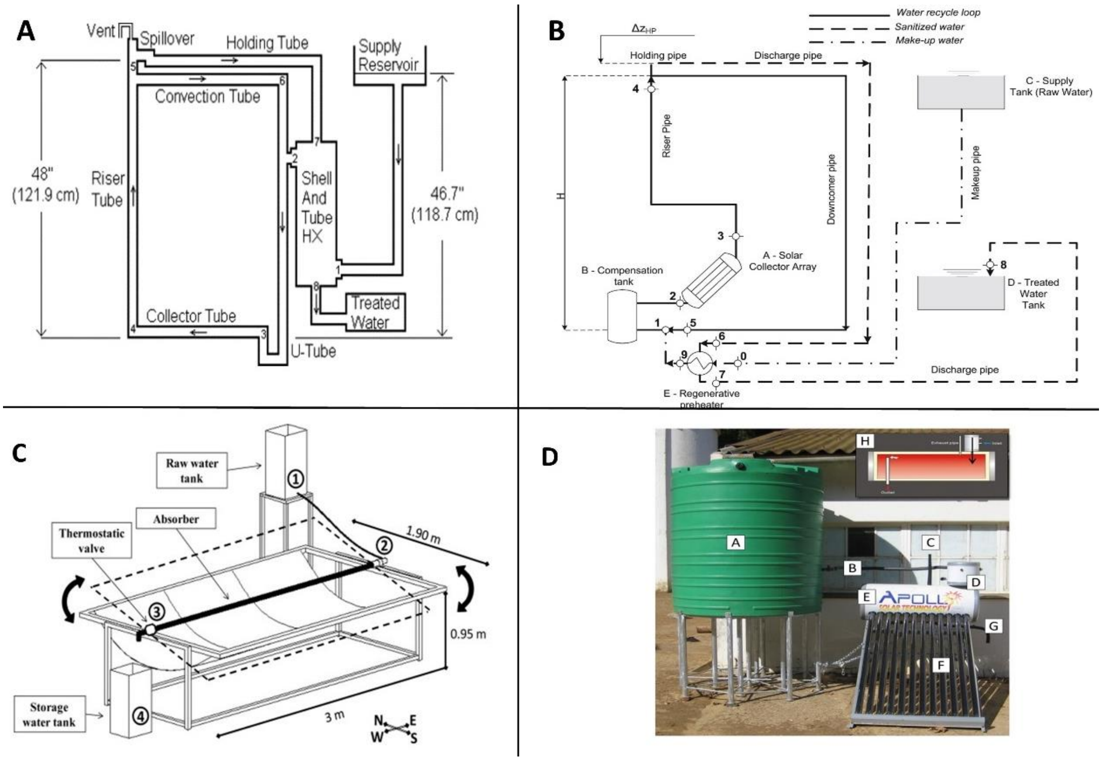


Figure 2: Heat-based solar disinfection systems. (A) Pasteurizer with natural water recirculation (Duff and Hodgson, 2005). “Solar Energy, 79, issue 1, Duf and D.A. Hodgson, A simple high efficiency solar water purification system, 25-32, Copyright Elsevier (2005).” (B) Pasteurizer designed by Duff and Hodgson

(2005) enhanced by Manfrida et al. (2017). “ENERGY Special Issue devoted to the 4th International Conference CPOTE 2016, Vol. 141, Manfrida et al., Natural circulation solar thermal system for water disinfection, 1204-1214, Copyright Elsevier (2017).” (C) Pasteurizer with parabolic trough concentrating collector (1, 2, 3, 4: four thermocouple probes) (Bigoni et al., 2014). “Journal of Cleaner Production, Vol. 67, Bigoni et al., Solar water disinfection by a Parabolic Trough Concentrator (PTC): flow-cytometric analysis of bacterial inactivation, 62-71, Copyright Elsevier (2014. (D) Low pressure pasteurizer. A: Raw water harvesting tank, B: Water feed into the inlet tank, C: Exhaust pipe, D: Water inlet tank, E: Main water storage tank, F: Collector tubes, G: Hot water outlet, H: schematic diagram of the interior of the storage tank, showing that the less dense heated water will rise and exit through the outlet (Dobrowsky et al., 2015). “Drinking Water Contaminants. Vol. 536, P.H. Dobrowsky et al., “Efficiency of a closed-coupled solar pasteurization system in treating roof harvested rainwater”, 206-241, Copyright Elsevier, (2015).”

Carielo et al. (2016) developed and tested a SOPAS semi-continuous flow system composed of a flat plate solar collector, a heat exchanger and an automation circuit. The automation circuit defines the treatment approach (temperature versus residence time), as well as controls the opening of the valves, installed at the entrance and exit of the collector (Fig. 3 A). At the end of the treatment cycle, the outlet valve was opened releasing the treated water and then closed. Then, the inlet valve was opened to allow the collector to be supplied with raw water, thus ensuring that the treated water was isolated from the contaminated water. The collector used had a capacity of 1.8 L and optical efficiency of 75%, the external part was aluminum, containing a simple glass cover with 2m^2 of opening area. The system was operated at different temperatures: 55, 60, 65, 75 and 85 °C adjusted for specific residence times for each defined temperature: 3600, 2700, 1800, 900 and 15 seconds, respectively. Inactivation of total coliforms and *E. coli* has been reported.

When the heat exchanger was not used, a maximum production of 30 liters per day was achieved, based on a critical solar radiation of 12.2 MJ/m^2. However, using the heat exchanger, a critical solar radiation of 8.3 MJ/m^2 was required, reaching a maximum daily production of 45 liters (Carielo et al., 2016).

Subsequently, using a flat plate solar collector MC 20C (Heliotek) (2 L capacity), the system was tested to disinfect water contaminated by other bacteria, achieving the inactivation of *Pseudomonas aeruginosa* and heterotrophic bacteria. Considering the 85 ºC treatment approach for 15 seconds of contact time, a maximum daily production of 80 liters was achieved (Carielo et al., 2017).

Amara et al. (2017) built a solar water pasteurization system in continuous flow, consisting of a parabolic solar disk measuring 1.3 m in diameter. In the focus of the concentrator was placed a flat collecting plate with 0.644m^2 of area, with a transfer capacity of 16KW, which is in contact with a fluid-filled chamber. A 14 mm diameter copper tube system allows the exchange of fluid-to-fluid heat (Fig. 3 B). An increase of more than 8.5 ºC in the raw water temperature was registered at a flow rate of 1 L/min.

Sizirici (2018) tested a flat-plate solar pasteurizer coupled to a slow filter (biossand filter) modified to disinfect spring water on a laboratory scale (Fig. 3 C). During the treatment, the water passed through the biosand filter (to reduce turbidity and microorganisms) and then through the pasteurizer to eliminate the rest of the microbial population.

The modified filter containing an extra disinfection layer with zero brave iron (ZVI, nano-Fe^0) was built as previously described by Yildiz. A volume of 4.62 L of the column was filled with sand, gravel and water, and the filter had a capacity of 0.4 L of water.

The pasteurizer consisted of a wooden box (40cm x 60cm) covered with aluminum foil, presenting 0.24 m^2 of opening area. A copper tube in serpentine with 7 mm internal diameter and 4.5 m in length, with a capacity of 170 mL, was placed inside the box. The copper tube and the aluminum foil were painted black and covered by a transparent double layer polycarbonate plate. The water outlet through the opening of the tube was monitored by a thermostatic valve regulated to open 75 ºC.

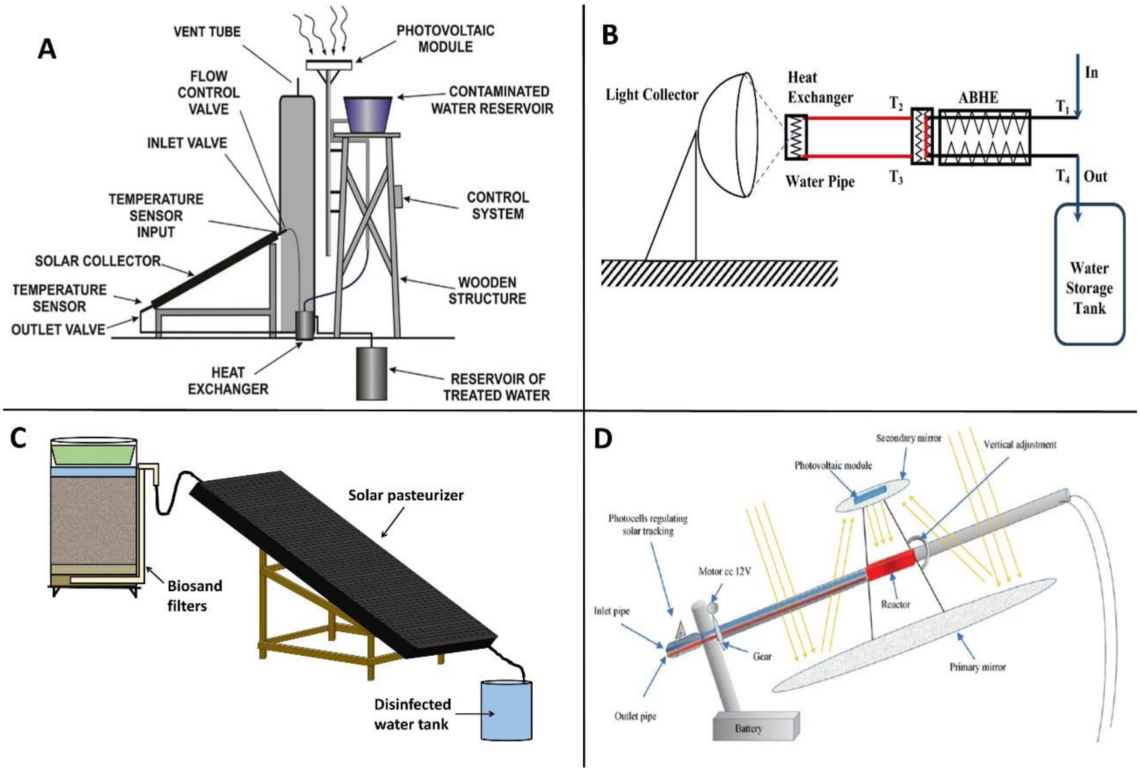


Figure 3: Heat-based solar disinfection systems. (A) Pasteurizer based on flat plate collector (Carielo et al., 2016). “Renewable Energy, Vol. 87, Part 1, Carielo et al., Solar pasteurizer for the microbiological decontamination of water, 711-719, Copyright Elsevier (2016)”. (B) Parabolic disk collector and fluid-to-fluid heat transfer device (Amara et al., 2017). “Renewable and Sustainable Energy Reviews, Vol. 70, Amara et al., Legionella disinfection by solar concentrator system, 786-792, Copyright Elsevier (2017).” (C) Bio-sand filter coupled to a flat plate solar pasteurizer. Drawing based on Sizirici's sketches (2018). “Journal of Water Process Engineering, Vol. 23, Sizirici, Modified biosand filter coupled with a solar water pasteurizer: Decontamination study, 277-284, Copyright Elsevier (2018).” (D) Continuous-flow pasteurizer based on a solar thermal disk (Domingos et al., 2019).

In the biosand filter, a reduction of 94.8% in turbidity was achieved, as well as a reduction of 1.65 $\log_{10}$ (96.25%) and 2.27 $\log_{10}$ (98%) of total coliforms and *E. coli*, respectively. In the pasteurizer 100% of *E. coli* and 99.99% of coliforms were inactivated by using previously filtered water and also unfiltered water. An average daily production of 4.5 L of pasteurized water was achieved. The author noted that after pasteurization, only previously filtered water had a level of turbidity suitable for human consumption, according to WHO`s drinking water guidelines.

Domingos et al. (2019) built a continuous-flow solar water pasteurization system, based on a disk-shaped double reflection Fresnel collector, measuring 3.8 and 1.3 m in diameter for the first and second reflectors, respectively. The disc was developed by improving the prototype patented by Cruz Y Bomant (2013) (Fig. 3 D).

The solar disk was automated to track the solar azimuth without the need to connect to the power grid. The solar radiation collected by the larger disk is concentrated in the smaller disk, which in turn concentrates the radiation in the reactor. The reactor is an aluminum block that surrounds tubular channels in the form of a coil, through which water flows. The water reached average temperatures between 58 ºC and 65 ºC on days with average solar radiation of 150 W/m^2, and the inactivation of *E. coli* was achieved at 60 ºC, with a flow rate of 63 liters per hour, remaining stable between 10 am and 3 pm under the conditions of southeastern Brazil.

The different designs of SOPAS-type continuous flow systems described (Table 2) can be improved or optimized to design solar water heating devices to be part of the high flow CFSSWD. For example, the drawing by Duff and Hodgson (2005) in its enhanced version by Manfrida et al. (2017), as well as the project by Carielo et al. (2016) (in its enhanced version with heat exchanger) can be improved by adding concentrating collectors such as those designed and tested by Bigoni et al. (2014), Amara et al. (2017) or Domingos et al. (2019). On the other hand, the addition of a tank for raw water and an isothermal heating tank (Main water storage tank) described by Dobrowsky et al. (2015) is desirable to improve the performance of the CFSSWD. However, the raw water must be filtered before accessing the raw water tank to remove larger particulate matter, and it must also be filtered more rigorously before the water passes into the filtered water tank (Yildiz, 2016).

4.2. SODIS-type continuous-flow systems

A continuous flow system for solar water disinfection was installed in a rural village in Kenya to treat water from a dam. The system was built according to previous specifications (McLoughlin et al., 2004) and consisted of compound parabolic concentrators (CPC), with pyrex tubes measuring 47.2 mm in internal diameter placed in the focus of the concentrators (Fig. 4 A). The total length of the tubular reactors was 120 m. The inactivation of 100% of the total coliforms in the water was obtained (from an initial concentration of 10^2 CFU / 100 mL), with a residence time of 20 minutes and a flow rate of 10 L per minute (Gill and Price, 2010).

Table 2: Profile of the main continuous-flow systems for solar water pasteurization.

Collector type	**Solar tracking**	**Collection area (m^2)**	**Water T ºC**	**Treated water (L/day)**	**Reference**
Evacuated tube	Stationary	0.45	~ 78	40 - ~160	Duff and Hodgson, 2005
Cylindrical reflector	1 axis	5.7	87	66 [a]	Bigoni et al., 2014
Evacuated tube	Stationary	0.96	64 – 66	72 [a,b]	Dobrowsky et al., 2015
Flat plate collector	Stationary	2	85	30 [a,b]	Carielo et al., 2016
Flat plate collector	Stationary	2	85	80 [a,b]	Carielo et al., 2017
Parabolic solar disk	1 axis	11.3	58 - 65	315 [a]	Domingos et al., 2019

Target microorganism tested: ([a]) *Escherichia coli*. ([b]) Total coliforms. TºC – Temperature

Mbonimpa et al. (2012) designed and built a continuous-flow reactor for solar water disinfection by UVB radiation. The reactor consisted of a quartz tube of 2.25 cm internal diameter and 127 cm long, placed in the focus of a compound parabolic collector, with 42 cm opening and 125 cm long (Fig. 4 B). The authors reported a significant reduction in the number of *E. coli* colonies, due to exposure of the contaminated water for 54.5 minutes.

Polo-López et al. (2011) built an automated system for solar water disinfection in a sequential batch. The system consisted of a compound parabolic concentrator, and in its focus, it was placed in a borosilicate tube with 89-90% transmittance in the UVA spectrum, equipped with electronic valves that controlled the flow in and out of the water. The tube was 1.5 m long, 0.05 m outside diameter and had a capacity of 2.5 L of illuminated volume (Fig. 4 C). The system was equipped with a photodiode to measure the dose of UVA. A software that calculated the dose of UVA and controlled the operation of the valves mediated the automation of the system. When the pre-programmed dose of UVA was reached to expose the batch of water, the valve opened allowing treated water to flow from the reactor to the storage tank and then the valve was closed. After the reactor was empty, the inlet valve opened allowing the reactor to fill with raw water. The inactivation of 6 $\log_{10}$ of *E. coli* and the production of 15 liters of disinfected water per day were reported.

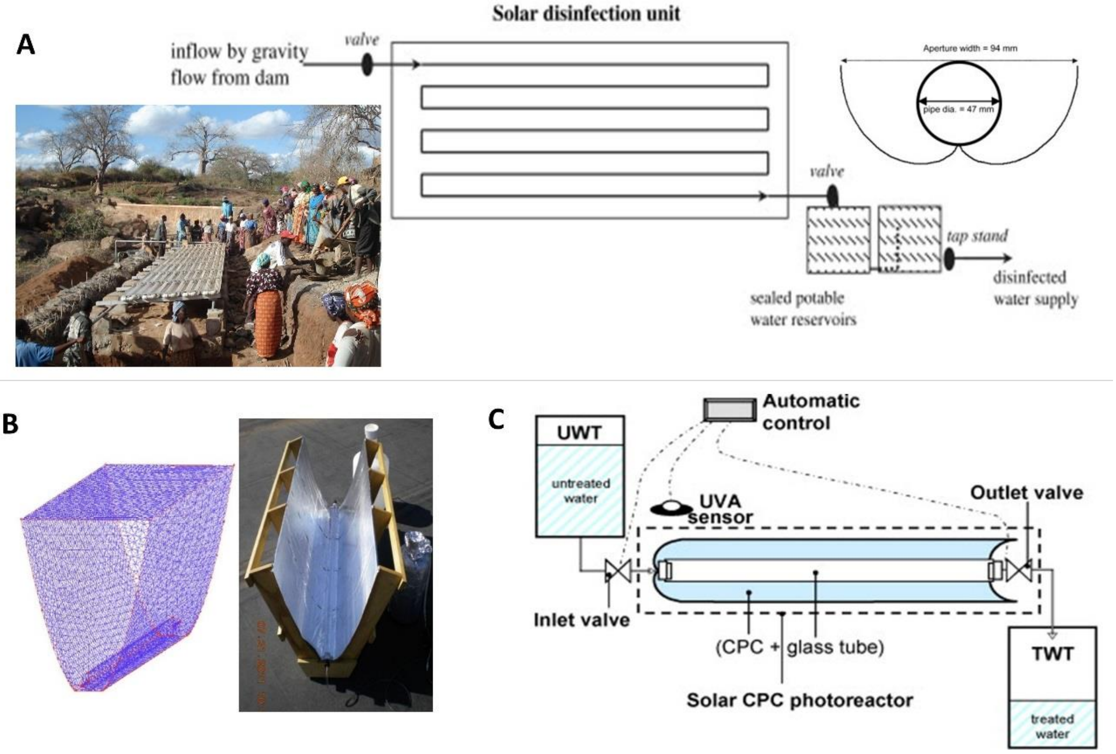


Figure 4: UV-based solar disinfection systems. (A) Installation of a continuous-flow system for solar water disinfection in a rural village in Kenya, scheme and profile of the solar disinfection unit and UV concentrator (Gill and Price, 2010). “The 3rd International Conference on Sustainable Energy and Environmental Protection, SEEP 2009, Vol. 35, Issue 12, L.W. Gill and C. Price. Preliminary observations of a continuous flow solar disinfection system for a rural community in Kenya, 4607-4611, Copyright Elsevier (2010).” (B) Computational grid (left) and the reactor for water disinfection by UVB solar radiation (right) (Mbonimpa et al., 2012). “Water Research, Vol. 46,issue 7, E.G. Mbonimpa et al., Continuous-flow solar UVB disinfection reactor for drinking water, 2344-2354, Copyright Elsevier (or appropriate Society name) (2012).” (C) Autonomous solar disinfection system in sequential batch (Polo-López et al., 2011). “Journal of Water Process Engineering, 196, M. I. Polo-López et al.

Elimination of water pathogens with solar radiation using an automated sequential batch CPC reactor, 16-21, Copyright Elsevier (2011)."

In our previous work (Chaúque et al., 2021) we developed a continuous-flow system for solar water disinfection, with recirculation, which combines the effect of optical and thermal solar radiation (UVA, UVB and heat). The system consisted of a heater and a solar UV irradiator. The heater was a parabolic trough concentrator with a thermo-absorbent tube placed in its focus; The UV irradiator was a Fresnel solar collector combined with a parabolic trough concentrator (Fig. 5 A). In the focus of the concentrators of the UV irradiator, tubular quartz reactors were placed, where the water circulates (Fig. 5 B). The system was tested to treat water with low or high turbidity (<1 or 50 NTU), previously contaminated by *A. castellanii* cysts and by *Escherichia coli, Salmonella* Typhimurium*, Enterococcus faecalis* and *Pseudomonas aeruginosa*.

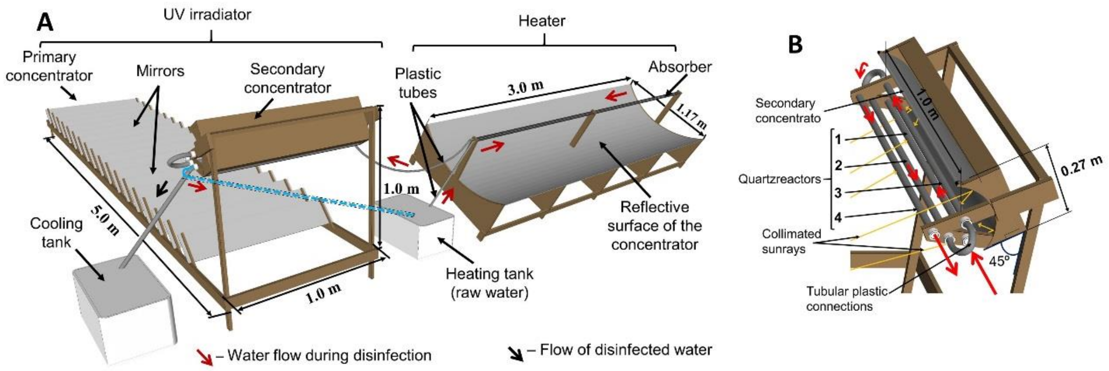


Figure 5: Continuous-flow solar disinfection system combining solar pasteurization (SOPAS) and a disinfection process based on solar UV radiation. (A) System overview, (B) details of the secondary concentrator (Chaúque et al., 2021). Springer Nature / Springer Link, Photochemical & Photobiological Sciences, A new continuous-flow solar water disinfection system inactivating cysts of *Acanthamoeba castellanii*, and bacteria, Chaúque et al., Copyright (2021).

The water flowed from the heating tank to the heater, then to the UV irradiator, and then returned to the heating tank, until it reached 45, 55, 60 or 70 ºC. After reaching the desired temperature, the water was kept flowing through the UV irradiator for 0.5 and 10 minutes.

The inactivation of all cysts was achieved by exposing water at 60 ºC to the effect of UV for 0.5 and 10 minutes, for waters with <1 NTU and 50 NTU, respectively. The inactivation of all bacteria was achieved when the water with <1 NTU or 50 NTU at a temperature of 55 ºC or 60 ºC, respectively, was exposed to the UV effect for 0.5 min.

5. Challenges for developing CFSSWD for large-scale water supply

The development of the CFSSWD for large-scale water supply depends on the improvement and successful integration of different technologies to increase the productivity of the solar water treatment process. The increase in productivity means the availability of large volumes of drinking water treated daily by each CFSSWD, ensuring the inactivation of microorganisms, including resistant ones. As previously discussed, and confirmed by several researches, the use of the synergistic effect of heat and solar UV radiation is more effective than the isolated use of heat or UV in solar water disinfection processes (Vivar et al., 2017; Chaúque et al., 2021). For this reason, the development of the CFSSWD must be based on the assumption that the system design must combine the properties of the SOPAS and SODIS processes. The technological improvements necessary for the development of CFSSWD for large-scale drinking water supply should mainly include the goals described below.

5.1. Solar collectors

The performance of any water disinfection system based on the direct use of solar energy is largely determined by solar collectors, as this is where the capture of solar radiation takes place, converting it into available internal energy to inactivate microorganisms present in the water contained in the reactor.

Solar collectors are basically classified into two types: concentrating and non-concentrating collectors. The collection area is generally the same as the radiation absorption area, in non-concentrating collectors (Jradi and Riffat, 2014). Details on the characterization of concentrating solar collectors can be found in the literature (Jradi and Riffat, 2014).

It has been widely proven that the use of concentrator-type solar collectors increases the effectiveness of SODIS and decreases the minimum exposure time required to achieve complete inactivation of microorganisms, which results in the treatment of large volumes of water per day (Navntoft et al., 2008; Alrousan et al., 2012; Gómez-Couso et al., 2012; Chaudhari et al., 2013). It has also been shown that the use of a reflector on the unlighted face of the reactor improves the efficiency of the conventional SODIS process, and this improvement was substantially greater in days of low sunshine (Mani et al., 2006).

Although non-concentrating collectors are very effective, and in some cases have a relatively higher cost benefit, in addition to being able to collect direct solar radiation and diffuse radiation. Concentrating collectors can achieve greater efficiency, allowing to maximize the flow of solar thermal energy with less losses by convection (Jradi and Riffat, 2014; Ullah et al., 2018). This makes concentration collectors a favorite in the development of CFSSWD heaters.

It has been widely demonstrated that in disinfection approaches based essentially on the optical properties of the sun, the use of collectors of the concentrator type has proved to be of great importance (Navntoft et al., 2008; Gill and Price, 2010; Polo-López et al., 2011).

The solar spectrum in the UV range occurs in the form of direct and diffuse radiation. For example, UVA radiation measured at sea level on sunny days is made up of about 60% direct and 40% diffuse radiation (Malator et al., 2009). Concentrating collectors use little diffuse ultraviolet radiation, so it is important that the CFSSWD is able to track solar radiation, preferably on two axes, that is, to make movements at an angle of 180º along its horizontal and vertical plane.

Therefore, the literature shows that the use of concentrators based on optics without image, called CPC, present a better performance in the concentration of direct and diffuse UV radiation (Malator et al., 2009). That is why CPC are preferred for the development of CFSSWD photo-collectors.

5.2. Reactors

The reactors described in the literature can generally be classified into two groups, thermal reactors and optical reactors (also called photoreactors), which are applied in the SOPAS and SODIS processes, respectively.

Thermal reactors are generally developed to work based on the physical properties of the blackbody (which absorb energy), and are made of different materials, such as steel, aluminum, copper and borosilicate glass. And they are generally painted in mat black, and in some cases are coated with different materials to minimize thermal losses by convection, for example clay or evacuated glass, when appropriate (Bigoni et al., 2014; Domingos et al., 2019; Dobrowsky et al., 2015; Carielo et al 2017; Sizirici, 2018). Although more research is needed to improve the efficiency of thermal conversion and heat transfer, in general, metal thermal reactors made of stainless steel or aluminum are the most recommended for their high performance, relatively low cost, high durability and for not oxidize. The inclusion of an evacuated tube transparent to solar infrared radiation (~ 760 - 1400 nm) around the thermal reactor, to avoid heat loss by convection is strongly recommended.

The optical reactors used in different devices for solar disinfection are generally made of materials transparent to light, and the reactors made of materials with high transmittance to UV radiation have shown better performance. Most optical reactors are made of materials such as PET, polypropylene, polymethylmethacrylate, borosilicate, quartz and pyrex (permeable to sunlight in the UV spectrum) (McLoughlin et al. 2004; Gill and Price, 2010; Ayoub and Malaeb, 2019; García-Gil et al., 2020; Chaúque et al., 2021). The literature shows that reactors made from pyrex are less effective than those made from borosilicate and quartz, however, although quartz has a higher transmittance than borosilicate, similar rates of bacterial photoinactivation yield have been reported (Ayoub and Malaeb, 2019).

In general, when designing high-performance CFSSWD, the option of optical reactors made of materials with high transmittance to UV radiation, such as quartz and borosilicate is strongly recommended.

The shape of the thermal and optical reactors varies according to the arrangement of the solar radiation beams in the focus of the concentrators, as a result of the configuration of the concentrator. Most of the solar thermal collectors described in the literature are cylindrical (Duff and Hodgson, 2005; Bigoni et al., 2014; Manfrida et al., 2017; Dobrowsky et al., 2015) or flat (Carielo et al., 2016; Carielo et al., 2017; Sizirici, 2018; Domingos et al., 2019; Chaúque et al., 2021). However, optical reactors equipped with concentrating collectors are predominantly linear cylindrical (Gill and Price, 2010; Polo-López et al., 2011; Mbonimpa et al., 2012; Monteagudo et al., 2017; Chaúque et al., 2021).

5.3. Heat exchangers

Heat exchangers are devices that allow the transfer of thermal energy from one fluid to another in heating systems, such as solar water pasteurization systems. In systems designed to use working fluids, the inclusion of heat exchangers is essential. The working fluid is a liquid that constantly circulates between the absorber (where it heats up) and the heat exchanger (where it transfers heat to raw water).

Installing a heat exchanger to reuse heat from pasteurized water to preheat raw water before entering the heating circuit substantially increases the productivity of SOPAS systems (Carielo et al., 2017). An increase of about 267% in the productivity of a solar pasteurizer has been reported after installing a heat exchanger in the SOPAS system (Carielo et al., 2016; Carielo et al., 2017). In addition, it helps prevent fluctuations in the effectiveness of thermal inactivation of microorganisms that could result from fluctuation in solar irradiation resulting from the transition cloud shading, as predicted by the inclusion of a compensation tank (Manfrida et al., 2017).

5.4. Water storage tanks

A variety of tanks, usually made of steel, concrete, plastic, fiberglass or other suitable materials, are used to store hot water, but those made of steel and plastic are commercially available in various sizes (McGuigan et al., 2012). The inclusion of an intermediate isothermal tank between the heating step and exposure to solar ultraviolet radiation is desirable (Fig. 13), since greater exposure to heat above the ideal temperature of microbial growth (> 45 ºC) makes microorganisms more susceptible to ultraviolet radiation (Rijal and Fujioka, 2001; Vivar et al., 2017; Chaúque et al., 2021), increases inactivation kinetics (Castro-Alférez et al., 2017) and prevents bacterial regrowth (Theitler et al., 2012). In addition, it will allow to maximize the use of ultraviolet radiation, as it will allow to maintain a constant flow of water in the optical reactor, since it will not be necessary to interrupt the flow to wait for the water to heat up, and this will contribute to an increase in productivity. Likewise, it is desirable for a diffuser to be connected to the end of the tube that conducts hot water to the intermediate tank, to allow mixing of the water and the homogeneous transfer of heat in the tank, so that the diffuser can spill the water nearby the surface of the base of the tank.

5.5. Mechanism for controlling disinfection conditions

Environmental conditions, such as temperature and radiation intensity, vary in space and time. However, the minimum conditions (for example, heat and UVA and B) established as necessary to achieve complete inactivation of microorganisms are immutable during the water treatment cycle. For this reason, the establishment of mechanisms to control disinfection conditions is desirable and necessary.

It is necessary to ensure that the water entering the system has an adequate level of turbidity. Thus, it is necessary that the performance of the filters (eg. Biosand filters) be monitored and that their maintenance is carried out with the necessary regularity. Likewise, it is essential to ensure that the water is at the proper temperature when entering the optical reactor and that it receives the appropriate dose of UVA and UVB radiation.

The installation of thermostatic valves is desirable, and independent electric valves are preferred. These valves must allow the reactors to empty and fill at different times to avoid cross-contamination, by mixing hot water and raw water (Bigoni et al., 2012; Carielo et al., 2016).

Mechanisms based on the density of fluids in a system of communicating vessels, which allow water to overflow after reaching a certain temperature, is a promising solution, as it is inexpensive and reliable (as it does not require moving components that can fail) (Duff and Hodgson, 2005; Manfrida et al., 2017).

The installation of a system to automate the monitoring of the dose of UV radiation and the opening and closing of valves is a desirable advance (Polo-López et al., 2011). This enhancement can also be used to automate the tracking of solar radiation on two axes by the CFSSWD.

In general, the UV radiation dose control system may be dispensable, considering that the availability of solar radiation high enough to heat running water, commonly coincides with the availability of an equivalent amount of UV radiation. Thus, the flow and residence time of the water must be adjusted to ensure that the water receives a minimum dose sufficient to achieve complete inactivation of the microorganisms.

This can be optimized by increasing the collection area and the concentration capacity of UVA and UVB radiation and using high transmittance reactors. The reactors must be long enough so that the water travel time is long, so that the water is exposed to high doses of ultraviolet radiation.

5.6. Water pretreatment

Pre-treatment steps aim to adjust some aspects of raw water quality to WHO's drinking water guidelines (for example, to reduce turbidity), as well as to reduce bacterial load and pathogenicity, and to increase the effectiveness of subsequent treatment steps (for example, increasing microbial susceptibility to SODIS) (Yildiz, 2016; Al-Jassim et al., 2018; Reyneke et al., 2020a).

Pre-treatment is of great importance if we consider the situation of the field mainly in regions where people do not have access to basic sanitation and modern drinking water systems. In such cases, raw water will need to be collected from rivers, springs, lakes or wells. The physical-chemical and mainly microbiological quality of the water in these sources can vary depending on the season, type of soil and whether there is sanitation infrastructure at the point of use (such as latrines and septic seals), or obsolete sewage systems nearby (Islam, et al., 2016; Martínez-Santos et al., 2017; Ngasala et al., 2019; Chaúque et al., 2021a).

5.6.1. Biological treatment

Reyneke et al., (2020b) briefly reviewed the combination of biological treatment with physical-chemical processes for water disinfection. This technique consists of inoculating the water with microbial predators (such as bacteriophages and predatory bacteria) to reduce bacterial density, and this water is subsequently treated through SODIS, chlorination, ozonation or filtration. (Islam et al., 2010). Although bacterial elimination through biological control has been successfully achieved on a laboratory scale (Wu et al., 2017; Obeng et al., 2016; Zhang et al., 2013), the expression of bacterial resistance to bacteriophages has been reported (Turki et al., 2012). However, exposure to bacteriophages has been reported to increase the susceptibility of bacteria to SODIS (Al-Jassim et al., 2018) and to decrease bacterial pathogenicity, as shown for *Pseudomonas aeruginosa* (Reyneke et al., 2020a). Further laboratory, pilot and field studies are needed to validate the effectiveness of this technique in practical situations.

5.6.2. Filtration

Water filtration can substantially improve the physical-chemical quality of water, in addition to allowing disinfected water to be suitable for human consumption (Yildiz, 2016; Romero et al., 2020).

A set of biosand filters can be built and installed to pre-treat raw water, removing particulate material, thus improving the physical-chemical quality, as well as the microbial quality by reducing the microbial density in the water (Romero et al., 2020; Maciel and Sabogal-Paz, 2020). Slow bio-sand filters are appropriate because they are effective, inexpensive and easily accessible.

Depending on the season, raw water can be highly turbid and have a high microbial load, especially if the population does not have access to basic sanitation services and uses latrines (Islam, et al., 2016; Martínez-Santos et al., 2017; Ngasala et al., 2019; Chaúque et al., 2021a). Although the high turbidity of the raw water favors the rapid saturation of the filter, it has been shown that the high turbidity improves the efficiency of bacteria removal, especially when the turbidity results from the suspended clay material (Romero et al., 2020). A slight decrease in the effectiveness of bio-sand filters is normally expected after maintenance (Maciel and Sabogal-Paz, 2020; Romero et al., 2020; Andreoli and Sabogal-Paz, 2020). It is recommended to install filters in sequence to allow filtration to be carried out in multiple stages, as in addition to improving performance (Medeiros et al., 2020) the maintenance of one of the filters in the sequence will not reduce the performance of the entire filtration of the device.

It is important that the filters are robust to remain stable during backwash unblocking, maintaining the integrity of the filter material layers of the filtration column.

It will be necessary to install an adequate number of filters, keeping it working day and night, and the filtered water must be stored in a tank, so that there is always water available to feed the CFSSWD.

5.6.3. Addition of small doses of chlorine

The addition of small doses of chlorine during the entry of water into the optical reactor is very advantageous, especially in adverse environmental conditions (such as days with partly cloudy skies), but still with relatively high UV radiation. When free available chlorine is exposed to solar UV radiation, it improves the effectiveness of SODIS, as it forms a variety of radical oxidants (such as $Cl^{\bullet}$, $OH^{\bullet}$, O_3), as well as transient forms of chlorine (for example Cl_2, Cl_3^-, $HClO^-$ ClO^-, Cl^-) (Zhou et al., 2014; Remucal and Manley, 2016; Paviet-Hartmann et al., 2002). These products resulting from the chlorine photolysis react quickly and non-selectively with different contaminants including biomolecules of microorganisms, causing their death, including chlorine resistant microorganisms, such as trophozoites and (oo)cysts *Cryptosporidium parvum* and of *Acanthamoeba castellanii* (Zhou et al., 2014; Chaúque and Rott, 2021).

While other technologies (e.g., ozonation, H_2O_2) also have an intensifying effect on solar disinfection, chlorine or chlorine-based disinfectants are preferred because they are cheaper, more accessible and practical to use.

5.7. New configurations of solar disinfection systems

The shortest way to develop CFSSWD for large-scale drinking water supply inevitably passes through the successful integration of the different technologies currently available, applicable in the solar water disinfection process. Among the priority technologies to be considered, we highlight those that allow increasing the efficiency of capture, concentration and use of solar radiation in the range of the infrared and ultraviolet spectrum. Equally important are technologies based on (nano) materials that allow the use of solar radiation in the visible spectrum, to effect the photoconversion of sunlight into heat, or to generate oxidizing radicals in water.

At this moment, the most urgent advance in the development of the CFSSWD is the development of systems with configurations that integrate the SOPAS and SODIS approaches, aiming to increase the efficiency and productivity of the systems (Fig. 6).

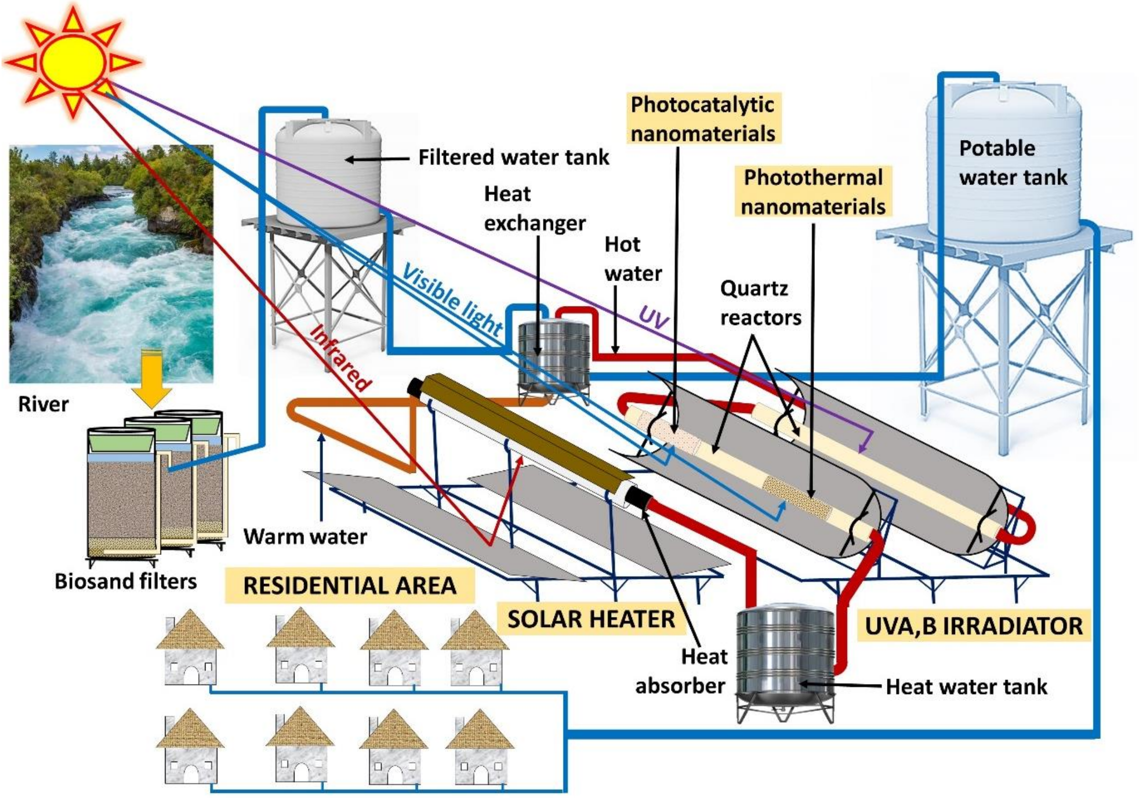


Figure 6. High performance continuous-flow system scheme for solar water disinfection.

One of the first continuous flow systems that integrated the photocatalysis and SOPAS approaches, reported in the literature, was tested for wastewater treatment (Monteagudo et al., 2017). The system consisted of

CPC collectors, in whose focus reactors of evacuated concentric borosilicate tubes were placed, the outer surface of the inner tube was coated with TiO_2 ($0.6 mg/cm^2$). This device was combined with a solar pasteurizer (Fig. 7). Water from the raw water tank flowed through the borosilicate reactors and then through the solar pasteurizer. The inactivation of 99.6% of $2x10^6$ CFU/ml of *E. coli* (during 80 minutes of residence) and the degradation of 30-70% of 5 mg/L of pharmaceutical antipyrine, were reported in the optical / photocatalytic reactor CPC. No CFU of *E. coli* was detected in the water leaving the pasteurizer controlled by thermostatic valves adjusted to open at 80 ºC (Monteagudo et al., 2017).

An advance in the integration of two approaches (SOPAS and SODIS) in a CFSSWD has been reported recently (Chaúque et al, 2021), some details of this system are presented in the text above. In this system, water flows from the heater to the optical reactor, and complete inactivation of bacteria and *A. castellanii* cysts has been reported.

Efforts need to continue to be applied to design, build and test different configurations of systems that combine SOPAS and SODIS approaches.

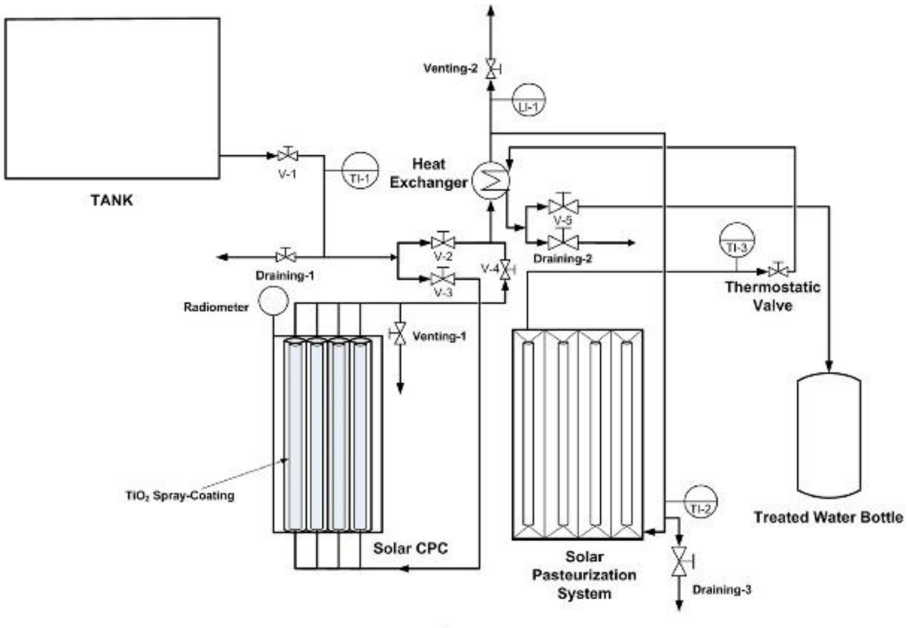


Figure 7: Configuration scheme of a continuous-flow system for solar water disinfection that combines Solar Pasteurization (SOPAS) and photocatalytic disinfection (Monteagudo et al., 2017). “Chemosphere, Vol. 168, Monteagudo et al., A novel combined solar pasteurizer/TiO_2 continuous-flow reactor for

decontamination and disinfection of drinking water, 1447-1456, Copyright Elsevier (2017).”

5.8. Disinfection processes based on nanomaterials

Great advances have been made in the last decades in the field of the application of nanomaterials in solar water disinfection processes, especially those involving photocatalytic and electrochemical disinfection (Huo et al., 2020). In addition, several researchers have reported an increasing number of new physical, photoelectric, photothermal and electroporate processes based on nanomaterials. The detailed description of the nature of these processes has not been included due to the scope of this review; interested readers are directed to the appropriate literature (Dutta et al., 2019; Verma et al., 2019; Huo et al., 2020).

5.8.1 Photocatalytic nanomaterials

Photocatalytic disinfection uses photocatalytic nanomaterials (PcNM) that, when exposed to the sun, promote the oxidation of water and certain substances present in it (for example, chlorine-based disinfectants), generating reactive oxidants (for example, O_3, $OH^{\bullet}$, H_2O_2) that react quickly and not selectively with biomolecules, as well as with organic matter and other solutes (Dutta et al., 2019; Remucal and Manley 2016; Patel et al 2019).

Resulting in the inactivation of microorganisms and degradation of chemical contaminants (for example, residues of pharmacological medicines and agricultural pesticides), eliminating them from the water body (Bossmann et al. 1998; Buxton et al. 1988; Kawabata et al., 2013; Remucal and Manley 2016).

The integration of this technology in optical reactors used in the CFSSWD needs to be considered. This will increase the severity of damage to microorganisms (Rizzo, 2009) and the effectiveness of the solar disinfection process (Lonnen, 2005; Gelover et al., 2006). It will also allow the water processed by the CFSSWD to be free of drug residues (Bosio et al., 2019), since these are present in almost all environmental matrices and mainly in water (aus der Beek et al., 2016; Patel et al., 2019).

A wide range of organic PaNM (e.g. vitamin B and erythrosine) and inorganic (such as titanium dioxide, graphene, silver, iron oxide, ZnO, Ruthenium) has been reported to be able to enhance the use of solar energy during SODIS (Alrousan et al., 2012; Ryberg et al., 2018; Lee et al., 2009; Snow et al., 2014; Helali et al., 2014; Mac Mahon et al., 2017; Shekoohiyan et al., 2019).

In general, PcNM-based solar disinfection processes show better microbial inactivation performance than SODIS alone. Different rates of microbial inactivation and drug degradation in water are reported in the literature, and these rates are greatly influenced by the concentration of PcNM, the physical-chemical composition of the water and the initial concentration of microorganisms (Lonnen et al., 2005; Rizzo, 2009, Bosio et al., 2019).

Recently, research has shown that PcNM configuration can be improved by combining nanomaterials with certain properties to build hybrid nanocomposite photocatalysts (eg, bismuth hybrids (e.g., Bismuth Hybrids ($AgI/Bi_{12}O_{17}Cl_{l2}$), Calcium Hybrids ($CaFe_2O_4/MgFe_2O_4$), Copper Hybrids (CuO/ZnO)) and increase the performance of photocatalytic processes (Li et al., 2015; Zhou et al., 2018; Lei et al., 2019).

The feasibility of integrating these materials in reactors for the CFSSWD needs to be evaluated according to their degree of adequacy. The following section presents the main criteria that need to be considered when selecting a PcNM.

5.8.2. Photothermal nanomaterials

Nanomaterials developed from photothermal nanomaterials (PtNM) (e.g., Au or Al nanoparticles coated with SiO_2 and carbon and chitosan nanoparticles) were applied to induce localized heating, without having to heat the entire volume of water, within a few seconds of exposure (Gao et al., 2019; Neumann et al., 2013; Zhou et al., 2016; Maddigpu et al., 2018). This allows a large volume of water to be processed in batch or in bulk, simply absorbing direct solar radiation to obtain the inactivation of microorganisms (Loeb et al., 2018).

The integration of this technology can significantly improve the CFSSWD, as it allows to significantly reduce the exposure time required to raise the water temperature to the desired level, before passing it through the UV reactors. In this case, only a smaller volume of water can be heated, at a time, in the amount necessary to pass through the optical reactors.

The PtNM can be immobilized on the surface of glass nanofibers arranged in the form of 3D meshes that cross the entire internal space of a tubular reactor with high transmittance to solar energy. This reactor can be placed in the focus of a solar concentrator, receiving water in continuous flow with optimized flow. The implementation of this description will allow the overcoming of several revised challenges, such as the difficulty of recovering nanomaterials (Lead et al., 2018; Huo et al., 2020).

5.8.3. Some notes on the integration of nanomaterials

The design of systems that integrate PcNM and PtNM needs to take into account the challenges that persist regarding the use of this technology. One of the main challenges is related to the fact that nanomaterials are very small, so they can be released into the effluents during the treatment process, leading to considerable ecotoxicity. In addition, research aimed at developing viable strategies to separate and recover nanomaterials, as well as to improve the performance, stability and durability of many nanomaterials remains necessary (Dale et al., 2015; Lead et al., 2018; Sun et al., 2016). The ideal is to build reactors that use immobilized nanomaterials, and that avoid direct contact of the nanomaterials with the water that is being disinfected.

The evaluation for the choice of the best PcNM or PtNM to be used in the improvement of reactors for CFSSWD needs to consider some qualifiers, such as: (1) Amount of reactive oxidants / heat generated per unit of measurement of PcNM / PtNM (the greater the amount of oxidants / heat generated, the better the PcNM / PtNM). (2) PcNM / PtNM stability and durability (the greater the stability and durability, the better the PcNM / PtNM will be). (3) Environmental toxicity (the less toxic and the less changes it causes in the environmental matrix, the more desirable PcNM / PtNM will be). (4) Accessibility and simplicity of the technology used for its use, maintenance and recovery (the more accessible and less complex the technology, the more desirable PcNM / PtNM will be).

6. Advantages and feasibility of CFSSWD

The advantages of high-flow CFSSWD are similar to those of conventional SODIS (McGuigan et al., 2012; Pichel et al., 2019), but without its limitations, enabling the use of solar disinfection as a large-scale public drinking water supply strategy.

It is important to note that the high flow CFSSWD is free from one of the main limitations of conventional water treatment systems, which is the high demand for electricity (Gude, 2015; Molinos-Senante and Sala-Garrido, 2017; Pichel 2019) allowing its applicability in several contexts, including in rural areas of developing countries without access to electricity.

It is understood that the development of high flow CFSSWD, enhanced by the integration of the technologies mentioned above, can increase the gross cost of production when compared to conventional SODIS. However, the cost-benefit ratio will be considerably higher if the number of people who can be served by each system is considered. And if we consider the advantages that it will bring, for example, the possibility of creating drinking water treatment, storage and distribution plants for communities. This will resolve several current limitations, such as increasing the load on domestic work with the routine required in the implementation of conventional SODIS, and the unavailability of reactors. Solar water treatment plants can provide access to drinking water on some rainy and cloudy days (depending on the projected flow rate, the daily water demand of the population and the capacity of the storage tanks), providing the surplus of treated water on sunny days. They will also significantly reduce uncertainty about the quality of water consumed by populations, allowing for a more accurate assessment of its impact on the health of the community, which would allow better decisions to be made when certain interventions prove necessary.

It is important to highlight that the implementation of water treatment and distribution stations based on the CFSSWD, in addition to helping to achieve the objectives of the UN's Sustainable Development Agenda (objective 6), can contribute to accelerate the development of poor countries. This will reduce the occurrence of water-borne gastrointestinal diseases (Graf et al., 2010; Clasen et al., 2015; Islam et al., 2015), often associated with malnutrition, low anthropometric measures, learning difficulties and high child morbidity and mortality, especially in rural and suburban areas (Berger et al., 2008; Semba et al., 2009; Gizaw and Worku, 2019; Bekele et al., 2020). The funds invested in mitigating and palliative measures can be used for other needy sectors, such as sanitation, food production and education.

7. Conclusion

This review aimed to explore the possibilities of applying solar disinfection (SODIS) as an alternative to large-scale drinking water supply, based on the technological advances currently available in the literature.

The smallest volume of water that can be treated per day, resistant microorganisms, intermittent availability of solar radiation, water turbidity and social barriers, are the main challenges that need to be overcome to allow the distribution of drinking water on a large scale using SODIS technology. A discussion of the impact and ways to overcome these barriers is exhaustively presented.

It was found that the application of SODIS as an alternative for large-scale drinking water supply, depends on the design of continuous flow systems for solar water disinfection (CFSSWD), whose configurations allow to combine the properties of SOPAS and SODIS systems.

The successful development of the CFSSWD depends on the improvement and optimization of the main constituents of the solar water disinfection system, including solar radiation collectors, photo and thermal reactors, heat exchangers, disinfection conditions control mechanism, pretreatment water and water tanks.

The integration and optimization of disinfection technologies based on photocatalytic and photothermal nanomaterials should also be considered.

Credit authors statement

The author: Beni J.M. Chaúque was involved in data collection, manuscript preparation, writing, and editing the manuscript.

Author: Marilise B. Rott was involved in the manuscript preparation and reviewing process.

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CAPÍTULO IV

Artigo intitulado “Development of solar water disinfection systems for large-scale public supply, state of the art, improvements and paths to the future – A systematic review” publicado na revista Journal of Environmental Chemical Engineering . https://doi.org/10.1016/j.jece.2022.107887. Detalhes da metodologia e parte dos resultados saõ apresentados no Apêndice XI.

Development of solar water disinfection systems for large-scale public supply, state of the art, improvements and paths to the future - A systematic review

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ABSTRACT

Solar drinking water treatment technologies are one of the most promising strategies to increase access to safe drinking water worldwide, as they are effective, affordable and sustainable. However, the development of affordable, high-performance solar water treatment systems applicable to large-scale public drinking water supply remains necessary. In this work, the state of the art in the development of solar water disinfection systems is systematically reviewed and a critical discussion is presented. Studies reporting high-performance solar water disinfection systems, or those capable of being upgraded for application in large-scale potable water supplies, were included. The solar disinfection systems described in the literature are of the SOPAS type (solar pasteurization), SODIS (solar disinfection by ultraviolet radiation) or mixed type (SOPAS + SODIS) and are based on concentrating or non-concentrating solar collectors. SOPAS + SODIS systems are more effective at microbial inactivation and, continuous flow or intermittent flow disinfection approaches in systems based on concentrating solar collectors or evacuated tubes are more productive. All systems reviewed can be improved, integrating or improving the concentration capacity of solar radiation, and increasing the efficiency of absorbers and/or reactors. Combining improved SOPAS and SODIS systems to develop mixed systems has been found to be one of the most important advances in the development of high performance systems. The integration of photovoltaic-powered artificial UV radiation disinfection technology as well as photothermal and photocatalytic materials into improved mixed solar disinfection systems needs to be explored. The performance of these systems needs to be evaluated in scenarios that simulate real large-scale water supply contexts.

Keywords: SOPAS, SODIS, Mixed systems, System configuration, High productivity of drinking water, Large-scale water supply systems.

1. Introduction

While considerable strides have been made in reducing the microbiological health risk associated with poor sanitation and unsafe water over the last century, due to greater access to centralized sanitation and safe water infrastructure, lack of access to safe drinking water remains a global concern. This results in the high prevalence of waterborne diseases attributed to biologically unsafe water consumption [1], especially in peri-urban and rural areas of developing countries [2,3,4]. It is estimated that the consumption of water collected from biologically unsafe sources by about 2 billion people worldwide is responsible for about 829,000 deaths annually, with more than half of these deaths (485,000) being caused by diarrhea [5]. These diseases and deaths are mostly prevalent in low- and middle-income developing countries and stand out among the most important causes of death in these contexts [6]. Lack of access, or difficulty in accessing safe drinking water sources, has been strongly associated with food and cases of child malnutrition [7,8,9], as well as the evolution of the health status of HIV-positive adults for AIDS [10]. This situation is explained by the fact that the majority (88%) of people who consume unsafe water live in low-income developing countries. Most of these countries are in Africa (53%) and Southwest Asia (35%), and in these contexts the contamination of drinking water sources is more prevalent in rural areas (41%) than in urban areas (12%) (Fig. 1) [3,4]. In addition, a considerable proportion of people considered to have access to safely managed drinking water services live far from these water sources and need to spend a lot of travel time (>30 min) to fetch water [11,12]. In developing countries, most of the population resides in rural areas and relatively less abundant urban centers are growing rapidly. These centers usually have extensive and dense periurban areas, often characterized by unplanned settlements, without basic sanitation infrastructure or drinking water. Interventions aimed at reducing the burden of waterborne gastrointestinal diseases in these contexts need to consider unconventional drinking water treatment technologies that are more accessible, cheaper and sustainable [3].

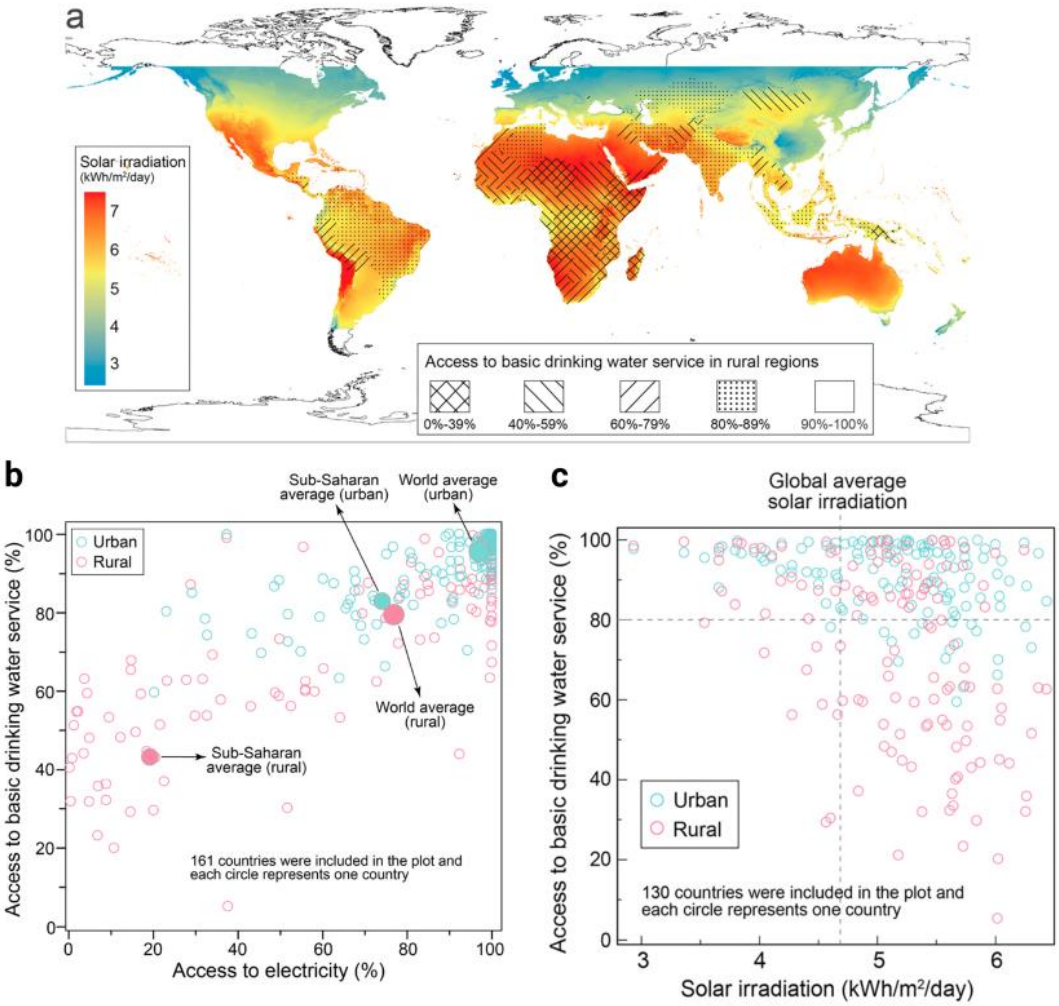

Fig. 1. Global status of access to drinking water sources in rural areas (a), and global and sub-Saharan African rates of access to basic drinking water services in rural and urban areas (b) as a function of average dose of solar radiation received annually (c), (adapted with permission, Copyright© 2019, American Chemical Society, [3].

While conventional methods of treating and distributing drinking water are effective and highly desirable as they allow for the treatment and distribution of large volumes of safe water and therefore supply large human settlements, they have limitations, which include inefficiency in removing some pathogens and the formation of undesirable disinfection by-products [13]. In addition, they have important economic and infrastructure limitations, as their installation, maintenance and operation are expensive, require chemical products, specialized labor and demand a lot of electricity. It has been estimated that an annual investment of $37.6 billion is needed to extend safely managed water services to underserved populations [14]. These aspects constitute barriers that are difficult to overcome in the context of low-income developing countries. In these countries, investments in other equally priority areas are needed and urgent, including, in health, education, sanitation, transport and security, while they need to face global challenges such as pandemics, terrorism and climate change [2].

On the other hand, technologies that use solar radiation to treat water have been widely proven as promising alternative means of providing safe drinking water to people with no access to safely managed drinking water sources [15]. The effectiveness and role of solar disinfection (SODIS) in combating waterborne microorganisms has been demonstrated on different fronts, from the elimination of microorganisms in water [15, 16], in the increasing the effectiveness of chlorine-based disinfectants [17,18,19] and in reducing the prevalence of waterborne diseases among children [20,21]. In addition, SODIS has been implicated in favoring immune responses that can result in the development of a state of resilience against waterborne pathogens and diseases [22,23,24]. The effectiveness shown by SODIS, associated with the fact that it is cheap, accessible and sustainable, justifies its listing among the alternative methods recommended for providing safe drinking water at a domestic level [5]. Coincidentally, the vast majority of countries with defiantly low rates of drinking water coverage are located in a geographic region that receives high doses of solar radiation throughout the year (Fig. 1) [3].

Although SODIS is an effective, cheap and widely used technology, it is not yet possible to use it as an alternative strategy for large-scale public drinking water supply, as a small volume (~2.5 L) of treated water can be available per day per batch through conventional SODIS. Conventional SODIS consists of placing untreated water in a container that is transparent to ultraviolet (UV) radiation (usually Polyethylene Terephthalate - PET bottle) and exposing it to the sun for at least 6 h (on sunny days) or for up to 12 h (on days with cloudiness of up to 50%), before consuming [15,25].

In the last three decades, and more intensely in the last two decades, considerable investment has been directed towards research related to SODIS and solar pasteurization (SOPAS) of water, as well as methods based on photocatalytic and photothermal (nano) materials applicable to drinking water treatment [26,27]. Likewise, a great deal of effort has been directed towards research aimed at increasing the volume of drinking water that can be made available daily through SODIS [28,29,30,31,32]. The increase in the volume of treated water made available per unit of time in the disinfection processes is a decisive step towards the application of this technology as a means of large-scale public drinking water supply. For this, it is necessary to develop solar water disinfection systems with configurations capable of maximizing the capture and use of solar radiation. The combination of SOPAS and SODIS and the integration of technologies based on photothermal and photocatalytic nanomaterials in solar water disinfection systems has been suggested as an important way to be considered in projects of high flow solar water disinfection systems [33]. However, the state of the art in the development of SOPAS, SODIS and SOPAS+SODIS systems needs to be thoroughly reviewed, and the way in which these systems (currently available in scientific literature and patent data base) can be improved and combined needs to be critically discussed. The synergy of heat (≥ 45 °C) and ultraviolet radiation from the sun [34], as well as the integration of photocatalytic materials [35, 36] have been implicated in accelerating microbial inactivation (including the inactivation of microorganisms resistant to conventional SODIS) during the SODIS process. It is important to emphasize that during the development of improved solar water disinfection systems, it is necessary to ensure that the technology generated is low-cost and accessible, if bringing clean water to low-income needy communities, especially in developing countries, is the goal.

The literature describes high efficiency systems applied in industrial processes that use solar thermal energy for electricity generation, food pasteurization and water heating [37,38,39]. Although it is possible to adapt these systems for potable water disinfection processes, their use in potable water supply plants for low-income poor communities would be practically impossible, as these systems are very expensive, since they demand large investments in infrastructure. Various SODIS, SOPAS and photocatalytic systems have been developed and tested on a laboratory and pilot scale. Many of them need or can be improved in order to increase their performance to make them applicable in solar drinking water treatment plants [40,41,42,43,44,45]. It is known that when a technology that increases the efficiency of capturing and using solar energy is integrated into conventional SODIS processes, performance increases. [46]. The state of the art in the development of high-performance solar disinfection systems needs to be reviewed.

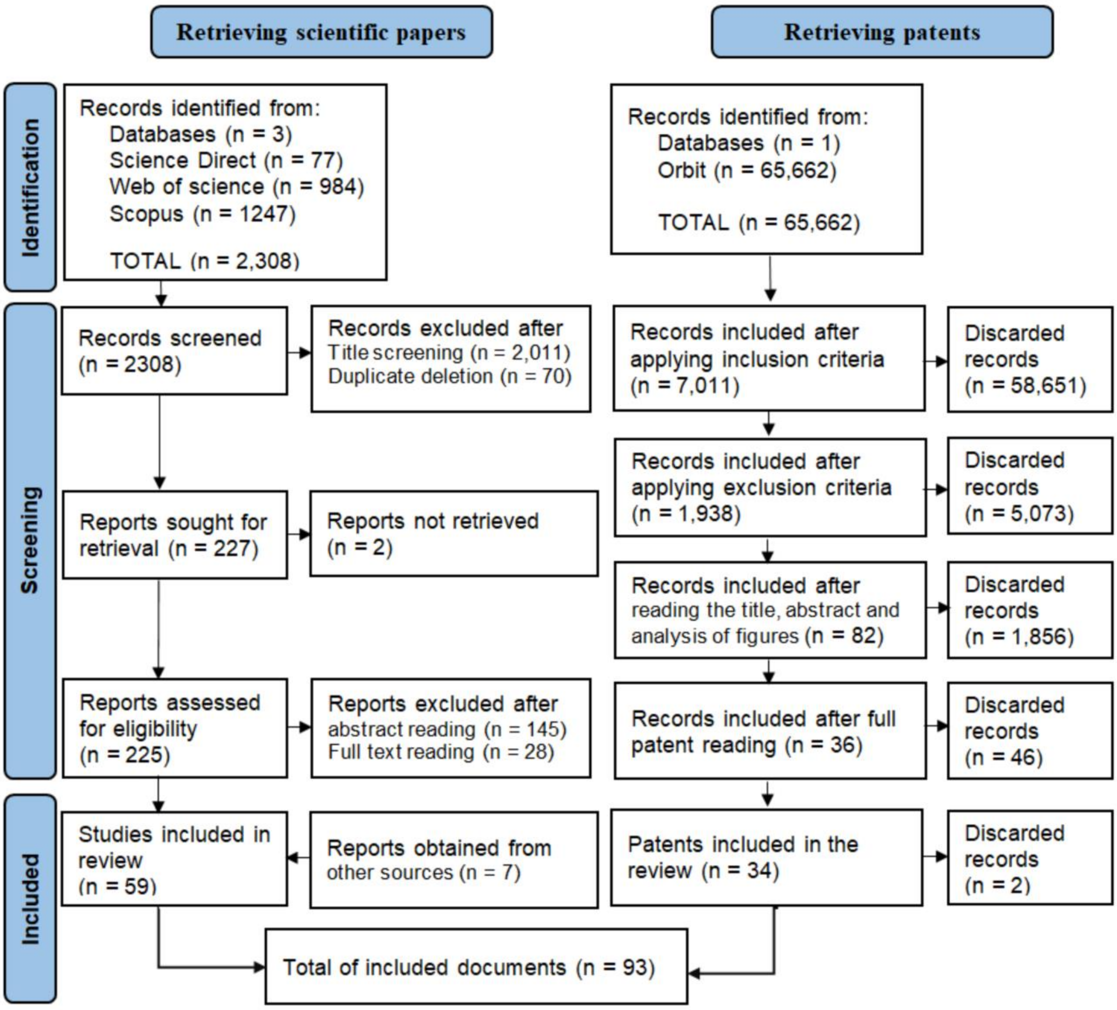

Fig. 2. Steps for collecting and processing articles and patents.

In the present work, the state of the art in the development of solar water disinfection systems is systematically reviewed. Priority was given to studies that describe systems that have the potential to be used (or can be improved) for the development of high performance systems applicable to large-scale water supply. The analysis and discussion focused on the configuration of the systems, specifically, the components for capturing and using solar energy in solar water disinfection processes. The discussion also tries to look for ways to improve the configurations of existing systems, or ways to develop new designs of solar disinfection systems with better performance, in light of the frontier of available scientific knowledge. The information reviewed in the present work was retrieved from scientific literature and patent databases, according to the strategies summarized in Figure 2 and detailed in the Supplementary Material.

2. State of the art in the development of solar water disinfection systems, where we are?

The solar radiation-based water disinfection systems described in the literature are essentially of three types, namely, solar pasteurization systems (SOPAS), systems based on the optical energy of the sun, commonly called solar water disinfection systems (SODIS) , and mixed systems.

SOPAS systems are based on technologies that capture thermal energy from the sun and convert it into internal heat that is transferred to water. When the temperature rises to values above the temperature tolerable by the microorganism for the minimum time necessary, it causes the inactivation of microorganisms present in the water.

SODIS systems essentially use ultraviolet radiation from the sun (UVA - 320-400 nm and UVB - 280-320 nm); in these systems the water is passed to reactors that are under the incidence of solar radiation. These reactors are made of materials that are permeable to ultraviolet rays, which allow microorganisms present in the water to be targeted by lethal doses of radiation. For microbial inactivation to be achieved, the water needs to remain exposed for an adequate time. Although SODIS systems essentially use solar UV, increasing the water temperature to values above the optimal temperature for microbial growth (≥ 45 ºC) increases the efficiency and productivity of these systems [34,35,47,48]. The mixed systems, in turn, have configurations that combine the mechanism of the SOPAS and SODIS systems (SOPAS + SODIS systems), allowing microorganisms present in the water to be exposed to the effect of heat and UV radiation during disinfection sessions. Mixed systems, in addition to being usually more efficient in inactivating microbes in water, ensure a safe inactivation of environmentally resistant microorganism structures (for example, cysts, oocysts and spores) and present greater potable water productivity for the same area of collection [33,49,50].

2.1. Solar water pasteurization systems

The solar pasteurization systems described in the literature are essentially of two types, systems based on non-concentrating collectors and those based on concentrating collectors. During operation, they can disinfect water by batch, sequential batch, or continuous flow with or without water recirculation.

2.1.1. Solar pasteurizer based on unconcentrated solar collectors

Pasteurizers based on unconcentrated solar collectors are essentially of two types, with flat plate collectors or evacuated tube collectors.

2.1.1.1 Solar pasteurizers based on flat plate solar collectors

Kang et al. [52] evaluated the effectiveness of a commercial solar heater to pasteurize chlorine-free tap water inoculated with *Escherichia coli* (5 - 7 log) (Fig. 3A). The system consists of a flat plate collector (measuring 2 × 1 × 0.1 m^3) connected to a heating tank (125 L). The movement of water (tank - collector - tank) occurs passively by convection. The cooler or less hot (denser) water found in the tank pushes the warmer (less dense) water found in the heat sink, causing it to rise into the tank; this cyclic process continues until a climax or thermal equilibrium is established. On sunny days with an average ambient temperature of 31 - 38 ºC, the average temperatures of ≥55ºC and ≥62ºC in the tank water were recorded after 2 and 4 h of exposure to the sun, respectively. At both exposure times, complete water disinfection was achieved. On cloudy or rainy days with an average ambient temperature of 28 - 30 °C, the average temperatures of 45 ± 4.2 ° C and 45 ± 3.5 °C were recorded in the tank water, after 2 and 4 h of exposure to the sun. Under these conditions, a 2 and 3 log reduction in *E. coli* viability was reported during 2 and 4 hours of exposure, respectively. Thus, the production of safe drinking water was only achieved on sunny days with ambient temperature >30°C [2].

El-Ghetany and Dayem [52] built and tested a solar water pasteurization system in intermittent flow, also based on a flat plate collector measuring 2.34 m^2 of collection area. The solar collector was equipped with a solenoid valve at the outlet and a heat exchanger was installed to recycle thermal energy from the pasteurized water. Modeling based on experimental data showed that the system is capable of processing 171 or 39 L of water per square meter of solar collector daily, considering a pasteurization temperature of 60 ºC or 90 ºC, respectively. The authors estimated that this productivity corresponds to 81.5 or 1.1 L/m^2 per kW/h of incident solar radiation, respectively.

Carielo et al. [53] built and evaluated a sequential batch solar pasteurization system, based on a flat plate solar collector, measuring 2 m^2 of collection area, and with optical efficiency of 75 % and a capacity of 1.8 L (Fig. 3B). The system was assisted by an automation circuit that managed the opening and closing of valves (inlet and outlet) as a function of predefined temperature and exposure time. Production of drinking water (according to WHO´s standards [2]) has been reported by reducing the viability of *E. coli* (4 log10 MPN/100 mL) to below the detection level (<3 MPN/100 mL) at various temperatures and exposure times (55 °C / 3600 s, 60 °C / 2700 s, 65 °C / 1800 s, 75 °C / 900 s and 85 °C / 15 s). A maximum production of 30 L per day was achieved when the system was operated without the use of a heat exchanger, however a daily production of 45 L was achieved when a heat exchanger was integrated. In the tests without and with the use of a heat exchanger, the following levels of solar irradiance were required to start the production of drinking water: ≥12.2 MJ/m^2 and 8.3 MJ/m^2, respectively. Subsequently, using a commercial flat plate solar collector (MC 20C Heliotek), with a capacity of 2.0 L, the system was tested to treat water contaminated by heterotrophic bacteria and *Pseudomonas aeruginosa*, operating at a temperature of 85 °C with an exposure time of 15 s, the double production (80 L) of pasteurized water per day was achieved. A residual bacterial viability and a disinfection efficiency of 95.3 - 99.9% have been reported [54].

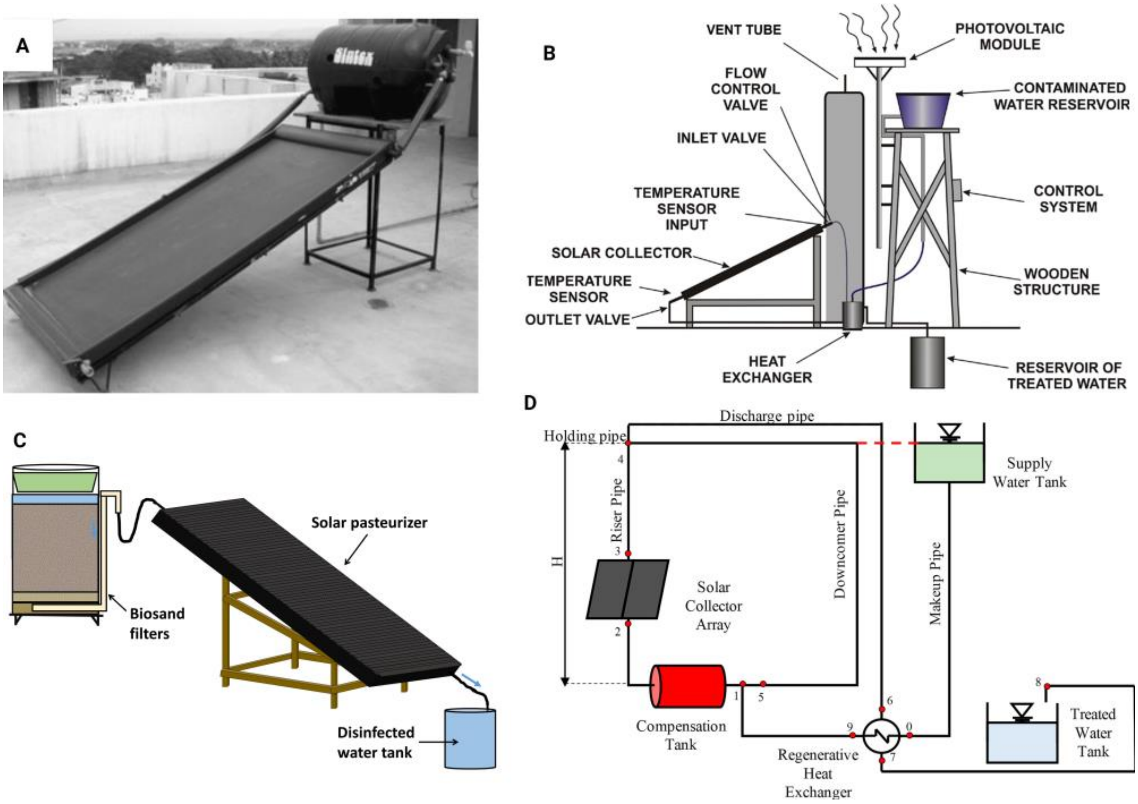

Fig. 3. Main configurations of solar water pasteurization systems based on flat plate solar collectors. (A) Solar Water Batch Pasteurizer ([51] License: 5163220818626). (B) Sequential batch solar pasteurizer with heat exchanger ([54] License: 5163130545305). (C) Sequential batch solar pasteurizer connected to bio-sand filter (Drawing based on Sizirici's [55] sketches, License: 5163131175107). (D) Continuous flow solar pasteurizer with convection recirculation, developed by Duff and Hodgson [61] enhanced by Manfrida et al. [62] ([68] License: 5163140160841).

Sizirici [55] built a laboratory-scale solar water pasteurizer based on a flat plate solar collector, which was tested to disinfect water previously filtered by a biosand filter (to remove turbidity and reduce microbial load). The biosand filter was improved with the inclusion of an extra filtration layer containing zero-valent iron (ZVI, nano-Fe0), whose construction details were described previously [56]. The structure of the pasteurizer was made of wood (measuring 40 x 60 cm^2) and had the shape of a box, which was lined with matte black painted aluminum foil, and its upper face was made of double-layer transparent polycarbonate board. A serpentine made of copper tube (painted black) measuring 7 mm in diameter and 4.5 m in length was placed inside the box

(Fig. 3C). The water left the pasteurizer when it reached 75ºC, which was the programmed temperature for opening the thermostatic valve installed in the opening of the serpentine. It was reported that the water leaving the biosand filter had a reduction of 94.8% in turbidity, in addition to a reduction of 96.25% (1.65 log) and 98% (2.27 log) in the total density of coliforms and of *E. coli,* respectively. Reduction of the viability of the remaining bacteria to below the detection limit was achieved during the passage of water through the pasteurizer. Although disinfection has been reported in the pasteurizer also for unfiltered raw water, only the filtered and pasteurized water met WHO's drinking water guidelines from the point of view of turbidity parameter (≤ 5 NTU) [2].

2.1.1.2. Solar pasteurizers based on evacuated tube solar collectors

Chao et al. [57] designed a solar water pasteurization system based on a vacuum solar collector tube, connected to a closed circuit. A working fluid heated by the solar heat collector heats a large volume of fluid contained in a heating tank. The heating tank works both as a thermal energy store and as a heat exchanger. The water leaves the raw water tank, passes through the coil immersed in the heat exchanger working liquid, where it is heated to safe temperatures for microbial inactivation, and then flows into the treated water tank.

Dobrowsky et al. [58] evaluated a commercial solar heater (Apollo™, from Apollo Solar Power Company), based on evacuated tube solar collectors, with 0.96 m^2 of collection area, for disinfection of rainharvested water. The solar collector consisted of 12 interconnected evacuated tubes, painted black and made of boron silicate glass. A reduction of faecal coliforms and *E. coli* (~10^2/100 mL) to density values below the detection level has been reported from temperatures of ≥72 °C.

Reyneke et al. [59] assessed the performance as well as the operational sustainability of microbiological treatment systems for rainwater harvested for public supply in an informal neighborhood in South Africa. These systems are solar heaters based on vacuum tube solar collectors connected to a pasteurization tank (with 125 L capacity), marketed by the PhungamanziTM company. Readers interested in the details of the operating mechanism of the system should refer to previously published literature [60]. Briefly, the raw water is made to flow to the pasteurization tank that communicates directly with the opening of each tubular collector. As the water heats up in the collectors, the hot water rises by convection and is replaced by cold or less hot water. The process continues until a maximum possible temperature (depending on environmental conditions) is reached. A prevalence of total coliforms, *E. coli*, fecal coliforms, and heterotrophic bacteria of 100%, 55%, 36%, and 100%, respectively, were reported from raw water samples during the monitoring period. A productivity of 10.84 L/h of safe drinking water has been reported (according to WHO standards [2]) considering solar irradiance of 1000 W/m^2 and disinfection temperature of 67 °C. No bacterial regrowth was observed in 100% of the treated water samples collected when the temperature of 66°C was reached in the pasteurization tank. The authors concluded that the systems were sustainable (since minimal maintenance was required) to provide an alternative source of drinking water, especially in the rainy season, in rural and peri-urban areas.

Duff and Hodgson [61] evaluated an innovative solar water pasteurizer, enhanced by incorporating a convection circuit, which allows water to move cyclically as it is heated. The system was based on evacuated tube-type solar collectors (with 0.45 m^2 of collection area) connected to a collector tube (Fig. 3D). When water becomes warmer (less dense) than colder water, it is pushed up through the riser and then into the convection tube, which in turn returns it to the header tube. This cycle is repeated, and the water temperature increases more and more until the overflow temperature is reached (~78°C). At this point, the water overflows, and the overflowing water is collected by the holding tube that leads to the treated water tank. Before reaching the treated water tank, the water passes through the heat exchanger, where it is pre-cooled while preheating the raw water. The tests were conducted under real environmental conditions with an incidence of solar radiation of 955 W/m^2. Under these conditions, a productivity of 19.3 L/h of pasteurized water was obtained. It is important to note that the overflow temperature in this system was regulated by the distance in height between the convection tube and the holding tube (3.2 cm), as well as the maximum height of the water in the raw water tank.

The system by Duff and Hodgson [61] was improved and submitted to performance evaluation by Manfrida et al. [62]. The improvement consisted of adding a compensation tank after the collectors to balance the water temperature in case of transient reductions in radiation incidence due to temporary cloud shading (Fig. 3D). Based on numerical simulations, these authors found that the system is capable of producing 40 to 80 L of pasteurized water per collecting surface (1 m^2) per day, depending on the solar irradiance of each geographic region.

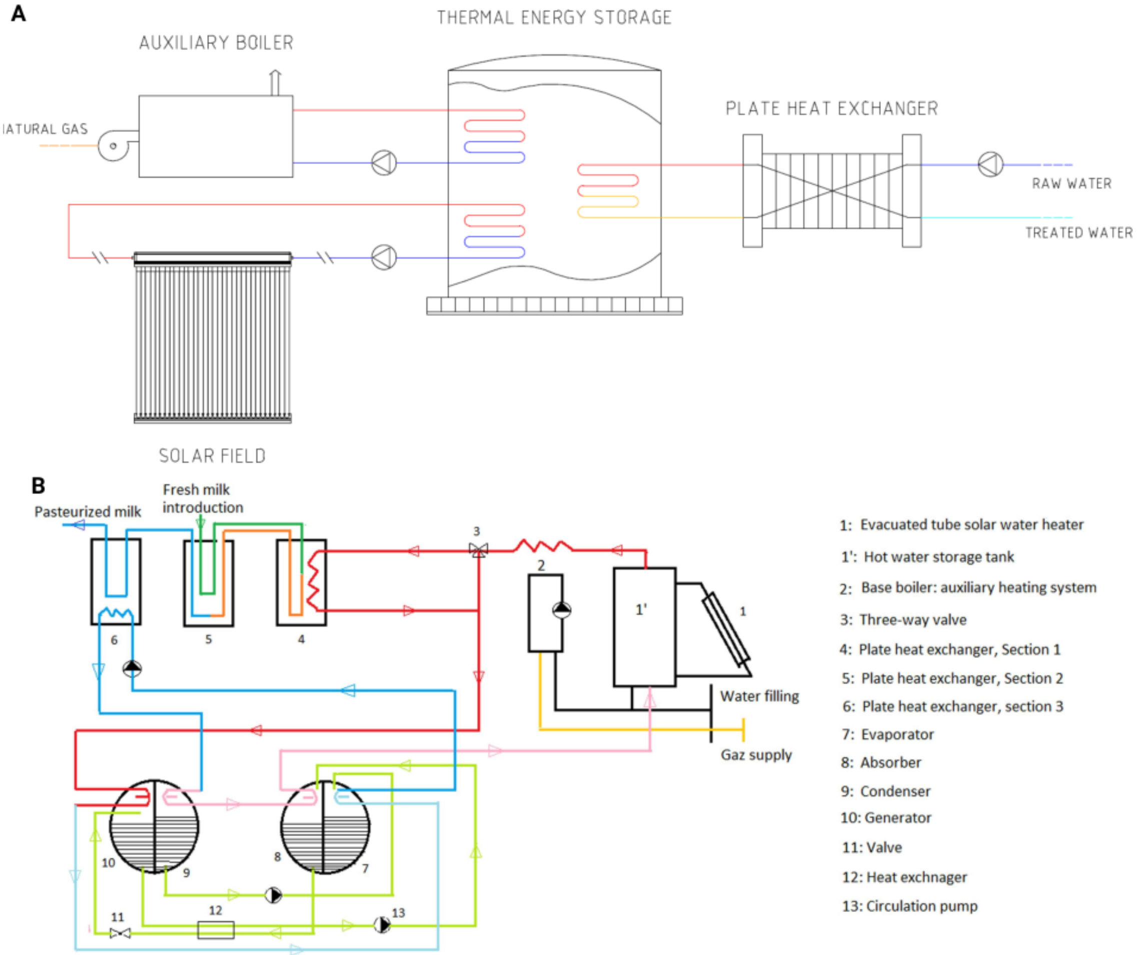

Fig. 4: Large-scale solar pasteurization systems, with thermal energy storage, based on tubular vacuum solar collectors. (A) Continuous flow solar potable water pasteurization system with auxiliary gas heater ([64] http://creativecommons.org/licenses/by/4.0/). (B) Solar continuous flow milk pasteurizer, based on heat exchangers, with auxiliary gas heater ([65] License: 5163140590199).

Ortiz et al. [63] compared the efficiency of two solar pasteurization systems based on evacuated tube collectors that have different thermal energy transfer mechanisms, namely, direct transfer (water on glass) and indirect transfer (metallic heat tube placed inside a glass tube). The collectors were connected in series in inclined planes, exposed to natural solar radiation. The water was made to flow through the collectors, and the different thermal variables (water temperature in the reservoir, in the inlet and autlet of the collectors and air temperature) were monitored. The indirect transfer collector (metallic heat tube placed inside the glass tube) proved to be 20% more efficient than the direct transfer collector (water in glass).

Bologna et al. [64] designed and estimated the cost versus productivity of a potable water treatment plant by pasteurization, based on thermal solar energy. A water heater powered by natural gas was integrated as an auxiliary source to level out the thermal fluctuation caused by the intermittence of the sun. The plant consists of three main parts, namely, solar thermal energy collection field (based on evacuated tube collectors), heat storage tank capable of maintaining a constant pasteurization temperature (75 °C) and a heat exchanger (Fig. 4A). These authors performed a laboratory-scale experiment before performing the system simulations, and observed that exposure of *E. coli*-contaminated water (10^3 NMP/100 mL) at a temperature of 75 ºC for 114 s caused bacterial viability to be reduced to below the detection limit. Based on these results, and considering a thermal energy storage capacity of 12 h, the authors estimated that the cost of production in installations with a flow rate of 50 L/s and 500 L/s is 0.32 and 0.25 euros, respectively, for each m^3 of drinking water treated. Furthermore, they reported that the use of solar thermal energy, as well as the increase in the duration of thermal energy storage leads to a reduction in the overall cost and price of the potable water produced.

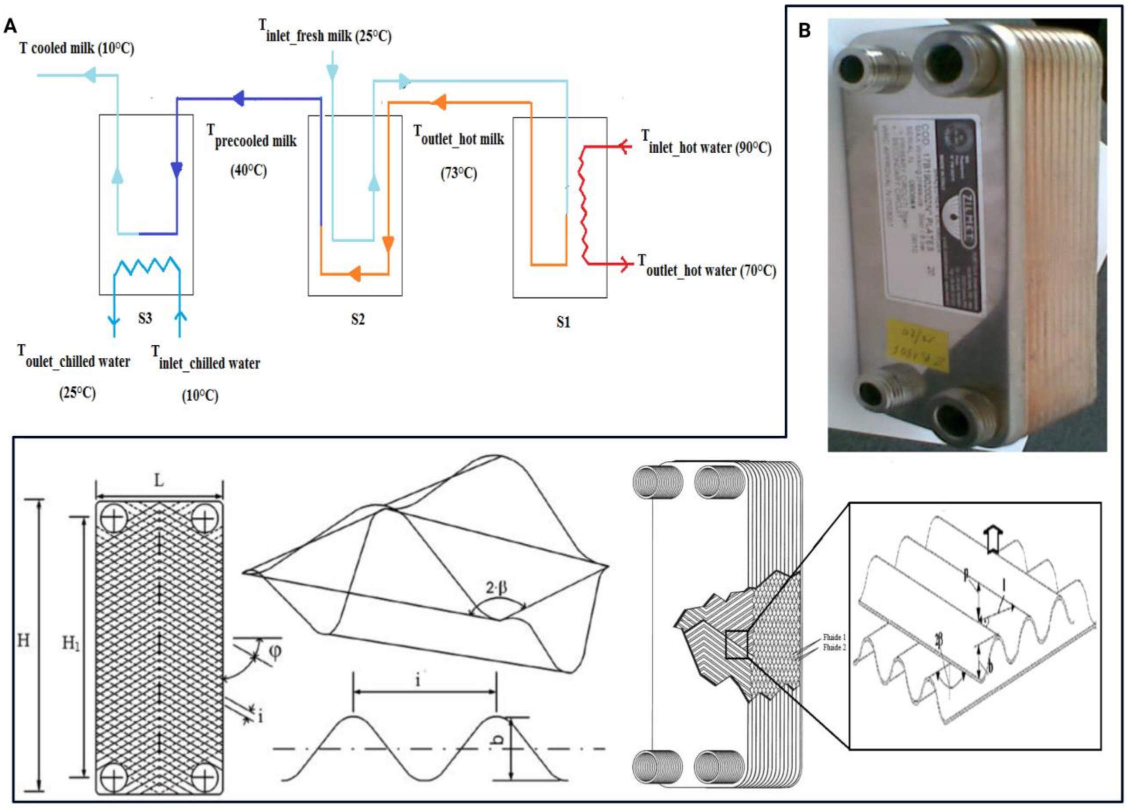

Fig. 5: Milk pasteurization circuit and details of the heat exchanger of the solar pasteurization system. (A) Sections of the pasteurization circuit, showing: S2 – the pre-heating / pre-cooling of the milk, S1 – the pasteurization and S3 – the cooling of the milk. (B) Details of the external ([65] License: 5163140883681).

An interesting solar pasteurization system was also developed by Lazaar et al. [65], although this system was designed for pasteurization of milk, it can be applied for water treatment. The system essentially consists of a solar water heater (based on tubular vacuum collectors), aided by a complementary heating system, a hot water storage tank, three sections of plate heat exchangers (S1, S2 and S3) and a refrigeration system (Fig. 4B). The heating system has the function of raising and maintaining the temperature of the water in the hot water tank around 90 °C. The water is conducted through tubes to the first heat exchanger, where the heat transfer takes place (between water and raw milk), allowing the temperature of the milk to rise to around 73 ºC. The pasteurized milk then goes to the second heat exchanger, where by thermal transfer it is pre-cooled and the raw milk that is in transit to the first heat exchanger is pre-heated. The pre-cooled pasteurized milk then flows through the third heat exchanger and is cooled to a temperature of 10 °C before flowing into the storage tank (Fig. 5A). These authors designed and tested a plate heat exchanger for the proposed system, which consists mainly of narrow channels (measuring 7 x 2.4 mm^2). Each channel is composed of two corrugated plates with beams slanted in the direction of the main flow (Fig. 5B). Experimental data showed that the efficiency of the tested heat exchanger varies according to the hot water inlet temperature and the flow rate. A maximum efficiency of 80% is achieved for an inlet temperature of 80 °C and a hot water flow of 386 L/h.

2.1.1.3. How to improve pasteurization systems with non-concentrating collectors?

A large number of solar water disinfection systems described in the literature are of the SOPAS type and use thermal energy from the sun to disinfect water. The vast majority of these systems (including commercially available ones) are based on non-concentrating solar collectors and, among them, flat plate collectors [52,53,54,55] and evacuated tubes [59,61,62,63,64,65] are predominant. Currently, solar water heaters based on high-efficiency non-concentrating collectors, applicable in water disinfection, are commercially available. These devices are especially suitable for regions facing economic and infrastructure challenges, and with lower demand per unit (<100 L / day) because they are relatively cheaper and simpler to install and operate [66].

The installation of thermally actuated valves (at the reactor inlet and outlet) ensures that the appropriate temperatures for microbial inactivation are safely reached in sequential batch disinfection systems [53,67], in addition to reduce the chances of microbial cross-contamination between disinfection batches. However, the presence of thermostatic valves in reactors has been associated with a greater environmental impact than systems without valves [68] in addition, the presence of moving components can increase the chance of system failures in addition to needing expert assistance and can increase system operating costs.

The integration of the heat exchanger has also been implicated in increasing the productivity of solar pasteurization systems [53,54]. Although the use of heat exchangers is desirable, as it makes it possible to recycle the thermal energy from pasteurized water to preheat raw water, their use must be careful. The care in the use of the heat exchanger aims not to increase the chances of survival of the microorganisms (whose viability was not irreversibly lost during the passage through the reactor) due to the rapid cooling of the treated water. Although it is desirable that 100% microbial inactivation be achieved within the reactor, the time the water temperature remains above the optimal microbial growth temperature after exiting the reactor is important to ensure the elimination of any residual microbial viability. This aspect is particularly important in a real-life situation where natural water normally contaminated by a variety of free-living microorganisms (including virus, bacteria, fungi, protozoa and helminths) is used as raw water. In these waters, certain forms of environmental resistance (ptozoan oo/cysts, bacterial and fungal spores and helminth eggs) may be present. These forms of environmental resistance are normally recalcitrant and often associated with the persistence of microorganisms (including pathogens) in treated water [69,70]. In this case, it is safer to install a heat exchanger in solar pasteurization systems that disinfect water by sequential batching, (including systems with a convection circuit, (Fig. 3D), since in these systems the admission of the water output of the reactor occurs when a constant temperature is reached. For continuous flow disinfection systems, it is recommended that pasteurized water has >60 ºC when leaving the heat exchanger, as this value corresponds to the thermal range reported as being ideal for the initiation of safe microbial inactivation [43].

In pasteurizers with non-concentrating collectors, disinfection of small volumes in sequential batch or continuous flow are better approaches to adopt [52,53] than disinfection of large batches [32]. These considerations are particularly correct from the point of view of the safety of microbial inactivation in water and the best use of available solar energy, especially in conditions of solar irradiance and medium to low ambient temperatures.

The integration of the convection circuit with the natural water circulation [61] improved by inclusion of a compensation tank [62] in solar pasteurization systems, in addition to reduce the environmental impact, by eliminating the use of thermostatic valves [68], it reduces the cost of manufacturing and maintenance, and increases the safety of microbial inactivation. During convection circuit integration, maintaining the water level in the raw water tank (to balance the natural water circulation) can be challenging, especially in large-scale solar drinking water treatment systems. This challenge can be overcome by installing floats that control the inflow of water from a larger tank to the secondary raw water tank connected to the convection circuit.

Several innovations that can considerably improve the performance of solar pasteurization systems based on unconcentrated solar collectors are described in the literature [71,72,73,74,75]. Xiaobing [71] developed a light supplementation device, which is coupled to the water storage tank of solar heaters based on evacuated tubes (Fig. S1A). The light supplementing device is a solar collector consisting of a box containing several rectangular channels. The inner surfaces of the channels are reflective, and one of the walls of the channels (the wall facing the sun) has three geometric configurations, starting with a flat oblique surface, then vertical and finally with a parabolic shape. Each row of channels leads to a parabolic compartment, which in turn opens close to the surface of a tubular collector. In this way, the solar radiation that falls on each collector channel is collected, concentrated and redirected to an area on the surface of the heater's tubular collector, resulting in an increase in productivity, due to the increase in collected solar energy. This device can be adapted to be used also in heaters based on flat plate solar collectors. Xiaohua [72] and Yun [76] developed an adjustable support, capable of changing the angle of inclination of the collectors to a position of maximum sun exposure, aiming to maximize the use of solar radiation by the water heater based on evacuated tube solar collectors. Xiyu [73] installed flat mirrors on both sides of the line of evacuated tube solar collectors, the mirrors were angled to reflect solar radiation onto collectors. Robert [77] proposed the assembly of compact solar heaters, based on flat plate or evacuated tube solar collectors (connected to water heating tanks) on a support containing rotating wheels, to allow tracking of the sun's position during the day. Subsequently, Suoxia et al. [78] developed a solar water heater based on evacuated tube solar collectors, capable of autonomously tracking the sun by rotation. This capacity is favored by the fact that the system is fixed on a mobile base, aided by a motor powered by electrical energy powered by batteries charged by photovoltaic panels. Information about the position of the sun in relation to the solar radiation collection plan is provided by a photosensitive sensor installed on top of the water heating tank. Huai [75] developed a solar focus device to increase the performance of solar water heaters based on flat plate solar collectors. The device consists of a succession of lens-shaped collectors containing a concave face and a flat face (Fig. S1B). The collectors are made of light transmissible material and the flat face faces the sun, so the radiation collected by each lens is concentrated in an area of the collector, thus increasing the heater's performance. Bingdong [74] developed a solar water heater based on evacuated tube solar collectors arranged in an inverted V shape. The heater consists of a water heating tank, connected on both sides to a row of evacuated tubular solar collectors fixed on an inclined plane (Fig. S2A). This configuration, in addition to increasing the collection area, maximizes the collection of solar radiation in both periods of the day (morning and after noon). Shengyu and Guanghui [79] in turn, built a similar system; however, the evacuated tube solar collectors were fixed in the focus of compound parabolic concentrators. Evacuated tube solar collectors as well as parabolic concentrators were placed inside a box made of thermo insulating material containing a face made of glass (Fig. S2B).

2.1.2. Pasteurizers based on concentrating solar collectors

It has been shown that the use of concentrating collectors in solar pasteurization systems significantly increases the water temperature in a shorter exposure time, and although the considerable increase in temperature also occurs in transparent reactors, the increase is more expressive when black colored reactors are coupled to collectors [80]. The concentrator type solar collectors described in the literature in solar water pasteurization systems are essentially of three types, flat, Fresnel type or parabolic. Parabolic concentrators, in turn, are of four types, namely, parabolic disc concentrator, parabolic dish concentrator, compound parabolic concentrator (CPC) and parabolic trough concentrator (PTC).

2.1.2.1. Flat, CPC and PTC concentrators

Alarcon-Herrera et al. [81] built a solar water pasteurization system, with sequential batch disinfection, which consisted of a spiral polyethylene tube (controlled by solenoid valves), placed under direct radiation incidence, as well as concentrated radiation by plane mirrors placed laterally on defined angles. A reduction in total coliform viability (22 x 10^3 MPN/100 mL) to below the detection level was achieved during 2 hours of exposure to solar radiation (sunlight intensity has not been reported). Pasteurized water met the WHO drinking water guidelines for the microbiological parameter [2].

Bigoni et al. [82] examined a solar water pasteurization system, which processes water in a sequential batch. The solar collector was of the PTC type and was made of polished aluminum sheets (with 5.7 m^2 area) (Fig. 6A). The heat absorber was made of black painted steel tube, which was fixed in the focus of the solar collector, and it was equipped with a thermostatic valve (at the absorber outlet) that opened and closed at 87°C and ~82.5°C, respectively. The system produced 66 L/day of treated water, inactivating *E. coli* (initial density up to 9 x 10^9 CFU/100 mL). Some potential residual bacterial viability was observed in samples incubated at 30°C for up to 72 hours. Although the microbial quality of the pasteurized water provided by these systems meets WHO's standards [2], it would need to be consumed within 2 days as potential bacterial growth has been reported after 3 days.

Yazdanbakhsh et al. [83] built and compared the effectiveness of three solar disinfection devices based on parabolic trough concentrator-type collectors, in the disinfection of water (0.50 and 100 NTU) inoculated with fecal coliforms (10^7 CFU/100 mL). A quartz tube (93 and 50% transmittance for UVA and UVB, respectively) measuring 105 m long, 3.5 cm outside diameter and 1.5 mm wall thickness, with a capacity of 1 L, was placed in the collector focus. While in device 1 the water was in direct contact with the reactor glass, in device 2 the water was contained within a black painted copper tube (measuring 100, 2.5 and 0.2 cm in length, width and thickness of the wall, respectively) placed inside the quartz tube. Device 3 was similar to device 2, differing only in that two flat mirrors (measuring 100 and 30 cm in length and width, respectively) were placed on each side of the concentrator, at a 45° tilt to increase the energy collection area (Fig. 6B). The tests were conducted on days with average sunlight and UV radiation of 930 and 27 W/m^2 respectively. Complete water disinfection (1 L per batch, with all turbidity levels) with no fecal coliform regrowth was achieved in all devices, but at different exposure times, and the disinfected water met the WHO's drinking water guidelines [2]. In device 1, complete water disinfection occurred within 90, 150 and 180 min (with maximum temperatures of 47.4, 53.2 and 57.1 °C, respectively) in water with 0, 50 and 100 NTU, respectively. In device 2, it occurred at 20, 25 and 30 min (reaching temperatures of 71.5, 74.9 and 77.1 °C). In device 3, the same result was obtained during 15, 20 and 20 minutes of exposure (reaching the temperature of 74.6, 78.2 and 80 °C) in water with 0, 50 and 100 NTU, respectively.

Laithong et al. [44] constructed and evaluated the performance of a continuous flow (without recirculation) solar water pasteurization system based on an asymmetric composite parabolic concentrator and a flat plate collector (Fig. 6C). The absorber is a box measuring 1.6 × 1.0 m^2, whose bottom is made of a sheet of zinc painted black and the top is covered with 5 mm thick glass. Inside the absorber, under the zinc sheet and 15 cm below the glass cover, a serpentine made of black painted copper tube measuring 8.11 mm in internal diameter was placed. The large reflector and the small reflector (located on the sides of the absorber) measured 1.6 × 1.2 m^2 and 1.6 × 0.5 m^2, respectively. The curve of the large reflector measured 1.35 m and the smaller reflector 0.6 m in length. The larger reflector was made of stainless steel, and on its back face was placed a coil of copper tube to take advantage of the heat conducted by the steel plate. During testing, water contaminated with *E. coli* (2×10^6 CFU/mL) flowed from the raw water tank, through the serpentine located on the wall of the larger collector, as well as the flat plate collector, and then flowed into the water storage tank. When the water flow was adjusted to 0.2 L/min, complete reduction of bacterial viability was achieved within 10 min of thermal exposure. The microbiological quality of the processed water was within the WHO's drinking water guidelines [2]. At this flow rate, the maximum temperature of 74 ºC at the outlet of the flat plate collector was reached and, on sunny days, the temperature of the water at the outlet remained above 55 ºC between 10 and 16 h.

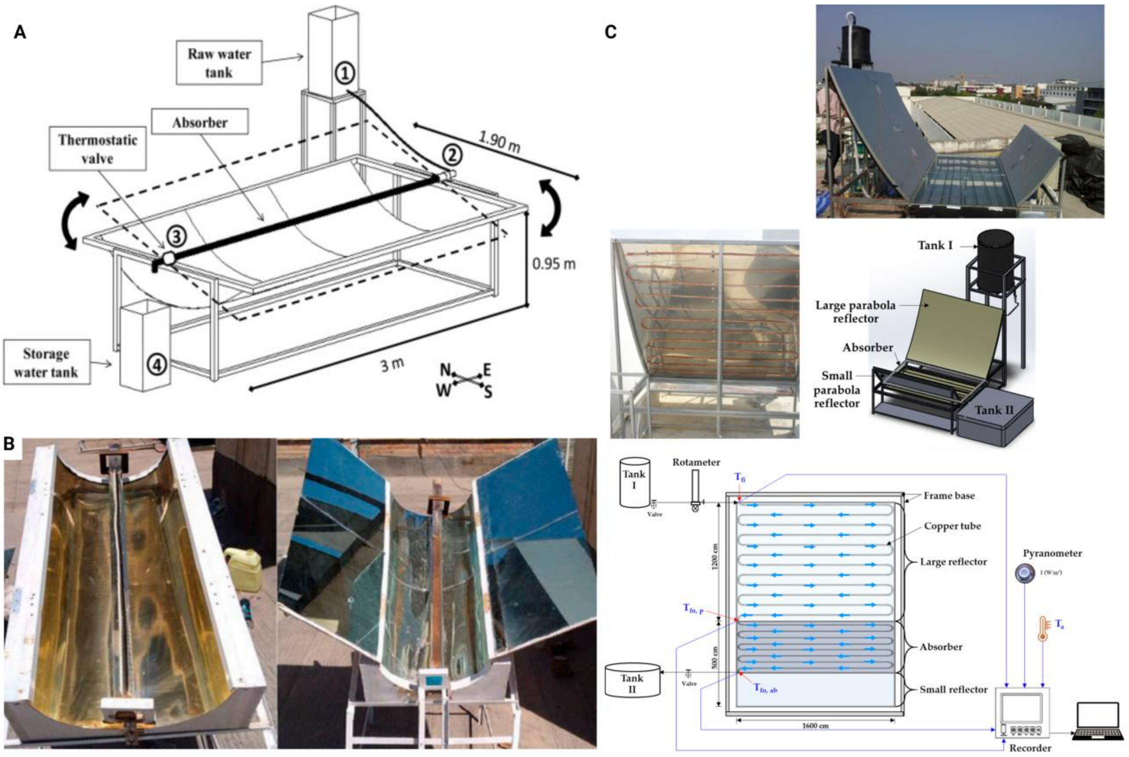

Fig. 6. Main configurations of solar water pasteurization systems, based on parabolic concentrator collectors. (A) Sequential batch solar pasteurizer based on parabolic trough concentrator (1, 2, 3, 4: thermocouple probes) ([82] Licence: 5163141387760). (B) Solar batch pasteurizer based on parabolic trough concentrator, without and with coupled plane mirrors [83]. (C) Continuous flow solar pasteurizer based on a composite parabolic concentrator and a flat plate collector ([44] https://creativecommons.org/licenses/by/3.0/).

Biencinto et al. [84] proposed and evaluated an innovative plant for the large-scale application of solar pasteurization in industrial processes. The plant is composed of a solar field based on parabolic trough concentrators, with characteristics previously described [85], a latent heat storage system (LHS) for solid-solid heat exchange, which uses pentaglycerin as a phase change material (PCM) and a heat exchanger (Fig. 7A). This plant was designed to provide thermal energy for pasteurization processes that use up to 85 ºC. During its operation, the solar field transmits thermal energy to the working fluid, which after reaching a minimum temperature of ~50 ºC, starts charging the LHS system with thermal energy. When the LHS thermal energy load reaches the minimum level to initiate solid-to-solid thermal energy transfer (~85 °C), energy begins to be passed to the heat exchanger. The heat exchanger is the energizing place of the industrial pasteurization process. When the energy storage system is fully charged, the industrial process can be powered directly by thermal energy from the solar field. When the energy made available by the solar field is no longer sufficient to meet the demand of the industrial process, the thermal energy flow is balanced by the LHS. It is reported that the proposed LHS has the autonomy to continue supplying energy to the industrial process for a further 3 h after the solar field is turned off. Although this plant was designed for milk pasteurization (with a flow rate of 11.11 kg/s) due to exposure to different temperature values, the system is applicable to the thermal disinfection process of drinking water, and for this case, it is expected a relatively larger volume of processed drinking water per day.

A system with a similar configuration was previously reported in the literature and was designed to disinfect wastewater by solar pasteurization [86]. The design of this system included the optional integration of a water heat recovery unit and an auxiliary heating source.

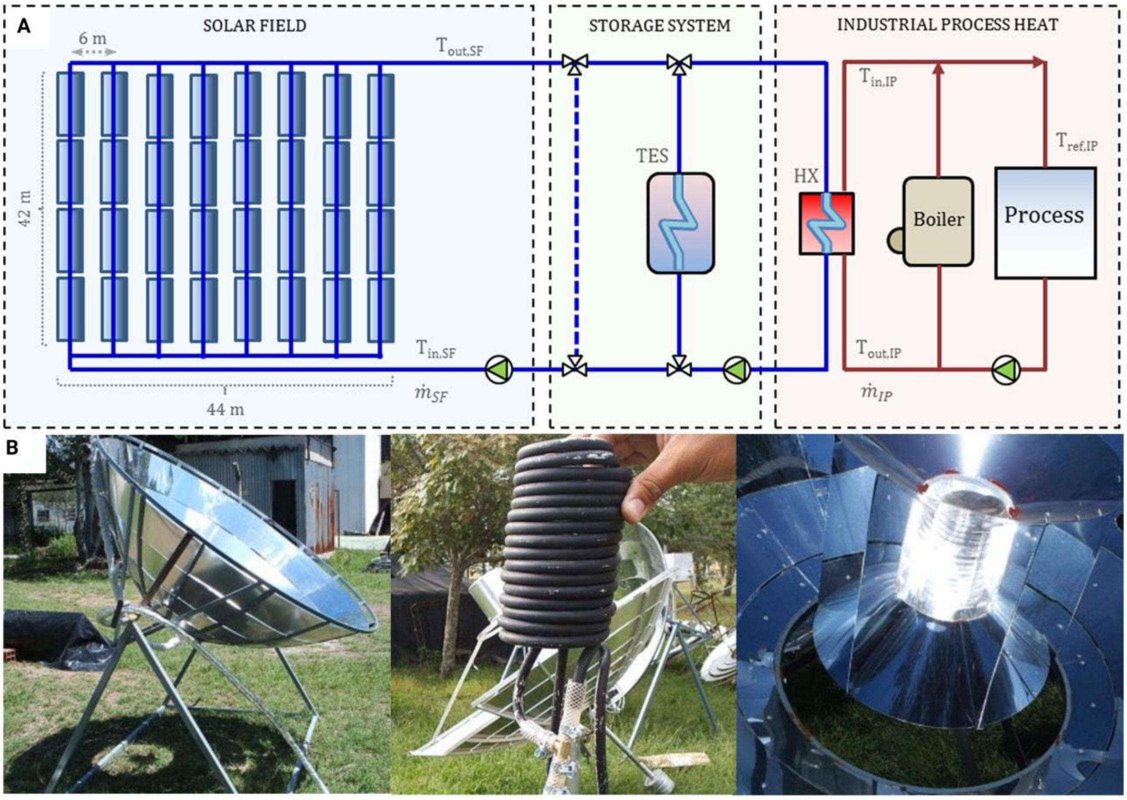

Fig. 7. Solar pasteurization systems based on parabolic concentrators. (A) Industrial scale solar pasteurization system, based on a solar field with CPC collectors and a latent heat storage system, for solid-solid heat exchange ([84] https://creativecommons.org/licenses/by-nc-nd/4.0/). (B) Solar milk pasteurizer,

based on a Fresnel concentrator with a parabolic dish arrangement, and an absorber in the form of a coil of double copper tubes ([87] Licence: 5163150958015).

2.1.2.2. Disc or dish-type concentrators

Franco et al. [87] built and tested a solar milk pasteurization system, based on a Fresnel-type concentrator with mirrors arranged in a parabolic dish, measuring 169 x 56.6 cm^2 in diameter and depth, respectively. A coil-shaped absorber made of black painted bronze tubes was placed in the focus of the concentrator, and it was installed inside a Pyrex glass mold to prevent heat loss (Fig. 7B). The device was used to generate steam, which in turn was transferred to a water bath containing a container of milk. The temperature rise to 65 °C was recorded in 75 min after focusing the concentrator, in a total volume of 15 L.

Morciano et al. [88] described an autonomous solar water heating system based on a parabolic dish-type concentrator with a heat absorber placed at its focus, and equipped to track solar radiation in two axes. A hydraulic circuit filled with working fluid (water glycol, which withstands temperatures of up to 110 °C) travels 8 m from the heat absorber to the plate heat exchanger (flow rate of 7 - 19 L/min), which is in contact with a 1000 L capacity thermo-insulated water tank. This system has been adjusted to keep the water below boiling temperature (90 °C). An average thermal conversion efficiency of ~65% has been reported, with peaks up to 78%. The integration of high-performance thermal energy storage technology was recommended by the authors to alleviate the mismatch between sun availability and users' hot water needs.

Amara et al. [89] built a continuous flow system (flow 1 L/min) for solar water pasteurization based on a parabolic dish-type concentrator, in whose focus a flat collector was placed. The collector is in contact with a chamber filled with a working fluid, which transfers heat to a thermal energy accumulator (Fig. 8A and B). A metallic tubular reactor submerged in the heat storage fluid receives raw water. The pasteurization of water takes place during its passage through the reactor. Pasteurized water exits the reactor through a heat exchanger before flowing into the treated water storage tank. Daily production of 160 L of processed water at temperatures of 51 - 57 °C (between January - June), 64 - 71 °C (between July - October), and 49 - 39 °C (between November and December) has been reported.

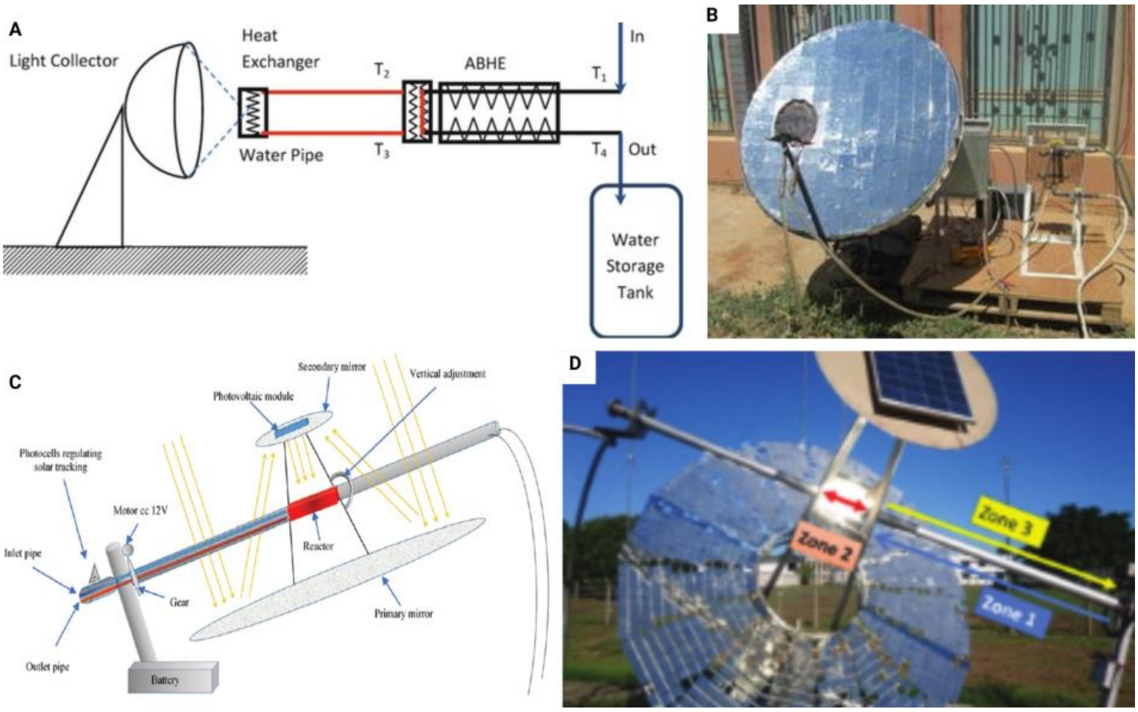

Fig. 8: Solar water pasteurization systems based on dish and disk type parabolic concentrator collectors. (A and B) Sketch and implementation of the solar continuous flow water pasteurizer based on parabolic dish collector, with fluid-to-fluid heat transfer device [89]. (C and D) Design and implementation of an autonomous continuous-flow solar water pasteurizer based on a parabolic disk-shaped double reflection solar collector [43].

Domingos et al. [43] built and tested a continuous flow solar pasteurization system, with autonomous solar tracking on one axis, based on a double concentration Fresnel disk concentrator. The collectors measured 3.8 and 1.3 m in diameter for the primary and secondary concentrator, respectively. The solar thermal energy collected by the primary concentrator is concentrated in the secondary concentrator, which in turn concentrates the radiation in the reactor, which is an aluminum block placed between the two concentrators. Inside the reactor, there are tubular serpentine channels through which the raw water flows (Fig. 8C and D). The system operated with a flow of 1 L/min, and average temperatures between 58 ºC and 65 ºC were reached on days with average solar radiation of 150 W/m^2. The reduction of *E. coli* viability (10^6 CFU/mL) below the detection level was reported from 60 °C, reaching a daily productivity of 315 L of pasteurized water.

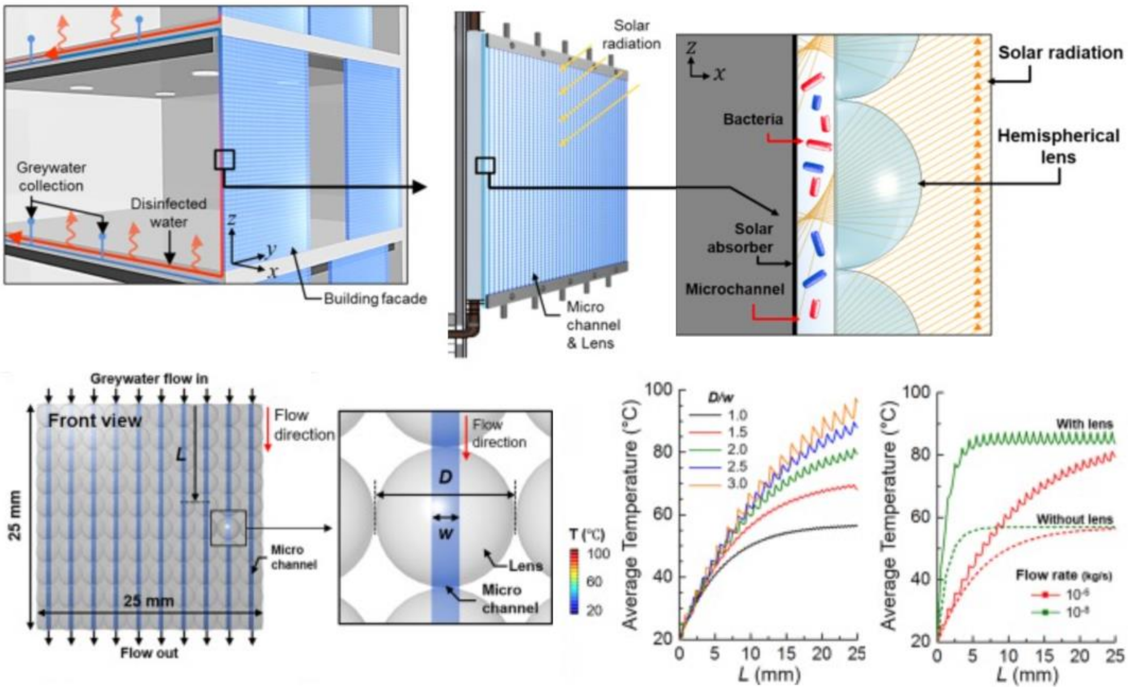

Fig. 9. Solar water pasteurizer based on a panel containing on its surface a series of microlenses that concentrate solar radiation and internal microchannels three times smaller than the microlenses. Water flows (with a flow of 10^{-8} L/min) through the microchannels and reaches >80 °C after traveling ~5 mm ([41] Licence: 5163190983719).

Kumar et al. [90] developed an interesting system that can be used as a solar water pasteurizer. The system is actually an indoor solar cooker, based on a set of parabolic dish-type solar collectors, combined with concave lenses, convex lenses and plane mirrors (Fig. S3). The solar collector is a funnel-shaped parabolic solar concentrator, which contains a convex lens placed in its opening. The solar radiation beams that fall on the collector's lens are caused to converge in a concave lens, which in turn transforms them into collimated beams. The collimated beams focus on a plane mirror placed at a 45° angle, which deflects radiation to the surface of another plane mirror which, in turn, deflects radiation to the surface of the heat absorber. The apparatus for collecting solar radiation is formed by several smaller units of collectors, arranged in a dome shape. This arrangement allows for static and passive tracking of solar radiation throughout the day and year. This system is similar to an innovation previously reported in the literature, aimed at carrying out the disinfection or photocatalytic degradation of contaminants present in fluids contained in pipes, including buried pipes [91]. The use of optical fibers to conduct solar radiation, including concentrated UV by parabolic-type collectors, to disinfect water in pipes and to treat human waste has also been reported [92,93,94].

Lee et al. [41] built an active panel based on solar optics (SOAP), to be installed on building facades, aiming at the use of thermal solar energy (for heating the interior of buildings) and for photothermal disinfection of gray water (used in showers, washbasins, etc.) by solar energy. The SOAP is composed of a flat plate with a transparent face, containing a hollow cavity in the form of microchannels through which the water circulates. The bottom surface of the board is black to maximize thermal energy absorption. On the transparent surface of the plate, which is the face facing the sun, there are several rows of concave microlenses (three times wider than the channels) that concentrate the solar energy, causing it to converge at various points along the length of the channels (Fig. 9). It was found that the greater the ratio between the lens diameter and the channel width, the greater the efficiency of the panel. The water that circulates through the canals is radiated by concentrated solar energy, causing an increase in temperature and microbial inactivation. There was an increase in temperature from the initial value of 20 ºC (inlet to the plate) to values between 75 ºC and 85 ºC, at a flow rate of 10^{-8} L/s, after the water had traveled 25 mm of the channel extension. Numerical simulations based on experimental data suggested that a inactivation rate of bacteria, including *E. coli* and *Enterococcus faecium*, could be safely achieved.

2.1.2.3. How to improve pasteurization systems with concentrating collectors?

Solar pasteurization systems based on concentrating collectors maximize the use of solar energy, as the solar energy received by a large area of the collector is directed to a smaller area where the absorber or reactor is located [95]. The concentration of solar energy allows the construction of a multitude of configurations of water disinfection systems that operate at high temperatures. The performance of solar pasteurization systems based on concentrating collectors depends essentially on the effectiveness of their mirrors in collecting infrared radiation, the efficiency of the absorber in capturing and transferring heat with minimal losses, and the entire circuit to use the collected energy for the desired purposes.

The ability of concentrators to track solar radiation plays an important role in increasing energy collection efficiency. Significant increases in solar energy uptake of 14.9% and 46.46% have been attributed to tracking of solar radiation by PTC collectors [96,97]. The state of the art of PTC collector technology, its constituents, materials used in its manufacture, as well as solar radiation tracking mechanisms and their application in industry, have been extensively reviewed [37,38]. During the design and construction of low-cost systems based on PTC collectors, with the ability to track solar radiation in two axes, it is interesting to consider the movement not only of the collector, but also of the collector's support platform. However, this improvement needs to be achieved by minimizing the inclusion of moving parts (to minimize the complexity, production cost and maintenance of the system) and without sacrificing the structure's robustness to withstand adverse environmental conditions such as high winds. The collapsible parabolic trough collector developed by Wei [98] can be an alternative to increase the resilience of concentrator collectors against climatic adversities such as strong winds and hail.

The combination of non-concentrating pasteurizers based on flat plate collectors or evacuated tubes with concentrators, as tested by Laithong et al. [44] (Fig. 6C) has great potential to increase the efficiency and productivity of solar pasteurization systems. However, the performance of this system can be considerably improved by replacing the flat plate collector used with the improved flat plate solar collector, such as the one developed by Sook [99] or by Xiaodong [100] (Fig. S4A). The use of flat mirrors placed on the sides of flat plate collectors to increase the solar radiation collection area and to increase the productivity of solar disinfection systems have already been successfully implemented [101,102]. The CPC collectors are particularly desirable (mainly in solar UV disinfection systems) for their greater acceptance angle and, in addition to their high performance when used in systems without solar tracking, they improve the use of diffuse radiation. However, despite these advantages, CPC collectors have a lower energy concentration ratio than PTC collectors [95]. The use of conventional CPC collectors in large-scale solar pasteurization systems can represent an economic and logistical challenge, because when seeking to increase the CPC concentration area, its height increases rapidly with increasing opening, making the support structure bulky and expensive. To solve this problem, Jadhav et al. [103] proposed an improvement in the CPC project, which consists of truncating its structure to substantially reduce its height, keeping it open, and without much compromising its ability to concentrate. These authors built and tested a system based on CPC collectors with an opening width of 2 m, a 3° acceptance angle, and a 48 mm outer diameter of receiving tube with a height of about 1 m. For the same aperture width, acceptance angle, and receiver dimensions, the height of the conventional non-truncated CPC is about 38 m. This drastic reduction in height also results in a significant reduction in CPC production costs. Steam production at 120 °C has been reported using the built-in system. A similar improvement has been shown previously in the literature [104]. This author has improved the CPC setup to increase the collection area and decrease the aperture shading due to the height of the collector. The enhanced CPC collector is a simple asymmetric truncated parabola facing the horizontal plane (Fig. S4B). When planning improvements to solar water pasteurization systems, it is also interesting to consider the innovation developed by Kaiyan and Hongfei [105]. These authors developed a solar water heating system containing a solar field based on evacuated tube solar collectors using boiling water as the working fluid. In this system, CPC collectors were mounted on the surface of the thermal energy storage tank (which at the same time functions as a heat exchanger) that concentrated solar radiation in an absorber located on the surface of the tank (Fig. S5). The use of flat point concentration or linear concentration collectors, such as those developed by Paul [106], Carlos et al. [107], Jung [108], Kim and Kang [109] and James et al. [210] on the surface of hot water tanks can be interesting. These collectors comprise a plurality of paraboloid mirrors arranged in the form of concentric circles (Fig. S6), and the collected radiation is concentrated in a conical light guide, which, in turn, concentrates the radiation at a point on the reactor surface [110]. When the parabloid mirrors are arranged in straight parallel lines, the radiation is concentrated in a linear focus [106].

In solar water pasteurizers based on CPC and PTC collectors described in the literature, linear absorbers fixed at the focal line are commonly used [82,83,84]. The best performing absorbers are usually metallic black and are usually placed inside quartz or borosilicate glass tubes to minimize convective heat losses [63]. The absorber configuration plays a big role in improving the efficiency of solar water pasteurizers. Readers interested in advances in the development of different configurations of solar absorbers, as well as possible improvements that can be made to improve their optical and thermal effectiveness, are directed to the appropriate literature [111]. The literature also presents two interesting configurations of V-cavity heat absorbers, not included in the above review, that have the potential to improve the performance of solar potable water pasteurizers based on CPC, or PTC, collectors. The heat transfer performance of the absorber with this configuration (Fig. 10A) was evaluated numerically and experimentally [112], and was reported to have high efficiency, as almost no sunlight escapes, even when reflected several times in its triangular opening. Furthermore, the rectangular fin absorber showed better heat transfer performance than the finless absorber. Subsequently, Rafiei et al. [113] examined a modified absorber, based on configurations previously described in the literature (Fig. 10B) [114]. The evaluation of the absorber's efficiency took into account different aspects, including the position, opening area and diameter of the V-shaped cavity, as well as solar irradiance, inlet temperature level and mass flow. It was found that the optimal cavity opening is 5, 5, 6, 7 and 8 cm (for optical errors of 5, 10, 15, 20 and 35 mrad, respectively), and that the highest efficiency is obtained when the absorber is positioned on the focal line of the PTC collector. Other authors reported that the turbulent flow of water through a cylinder-shaped solar absorber twisted into a helical shape allowed reaching maximum water temperature values. And although the high performance of solar heaters using twisted cylindrical absorbers made of any material has been reported, a higher yield was obtained when absorbers made of copper were used [115].

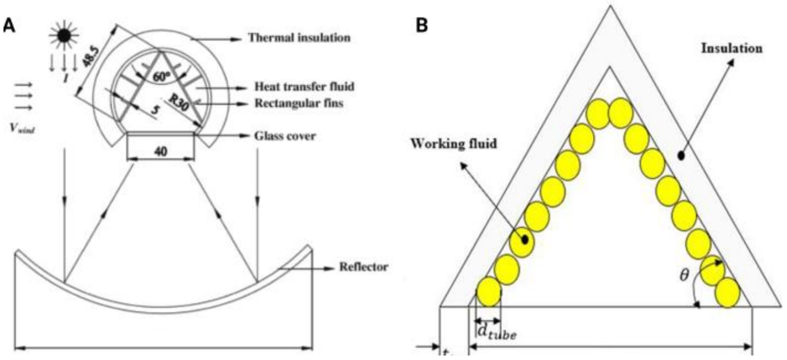

Figure 10. Thermal absorbers with a V-shaped cavity. (A) Absorber in a semicircular tube with channels, in contact with the anterior face of a V-shaped cavity ([112] License: 5163230917419). (B) V-cavity absorber containing tubes placed on the front face of the opening ([113], http://creativecommons.org/licenses/by/4.0/).

Solar pasteurization systems based on a parabolic dish type collector, described in the literature, have a great potential to be applied in the disinfection of drinking water for low-cost community supply. These systems are particularly desirable as they can work to their full potential by tracking solar radiation along just one axis throughout the day. The autonomous solar radiation tracking strategy validated by Domingos et al. [43] can be widely used because, in addition to increasing performance, it allows the system to be autonomous, and only some alignment adjustments may be necessary throughout the year to compensate for the misalignment resulting from the earth's translation movement. Many systems described in the literature have the potential for high productivity of safe drinking water [42,87,88,89]. However, improvements to increase the residence time of water, and ensure that an adequate minimum temperature capable of eliminating microorganisms is reached, remain necessary, particularly in continuous flow disinfection systems. The integration of high-performance heat exchangers can significantly increase the productivity of these systems [53,65]. The design, construction and use of polymer heat exchangers for solar pasteurization systems as an alternative to metal has been suggested to reduce production costs [116].

A multitude of solar potable water disinfection system configurations, including enhanced pasteurizers, can be developed from the solar pasteurizer developed by Lee et al. [41] (Fig. 9). For example, a panel with two transparent faces, containing a black central wall, can be constructed and placed in the focal area of the Fresnel concentrator (in place of the secondary concentrator in the system developed by [117] while the other face receives direct solar radiation. This panel can also be placed in place of the PTC of the pasteurizer (device 3) tested by Yazdanbakhsh et al. [83], or in place of the flat plate solar collector placed in the solar pasteurizer built by Laithong et al. [44] (Fig. 6B and C). A dome-shaped parabolic solar pasteurizer can be built using this panel and this will make the system work with passive tracking of solar radiation at all times of the day. In addition, the transparent parts of the panel, including the microlenses, can be made of material with high UV transmittance (e.g., borosilicate, quartz, pyrex), and thus a high-efficiency reactor for mixed solar water disinfection systems based on synergy of heat and UV will be obtained.

Integrating thermal energy storage systems is an important step to consider when sizing from single-family systems to large-scale supply systems. The use of thermal energy storage allows energizing the disinfection processes of medium to high flow, with high and constant energy delivery, thus allowing stability and the establishment of a standard of functioning and quality of the process. The projects examined in the literature that integrate the thermal energy storage mechanism have a high potential to be used effectively in large-scale and low-cost drinking water supply [64,65]. However, the need for a high initial investment as well as an auxiliary heater powered by natural gas can be a challenge, although the intensity of use of this auxiliary heat source may vary depending on the size of the solar field and the intensity of the radiation that varies with geographic latitude. On the other hand, the project developed and evaluated by Biencinto et al. [84] is independent of an auxiliary heater and integrates a latent heat storage system for solid-solid heat exchange that uses pentaglycerin as the phase change material. These authors experimentally demonstrated that pentaglycerin is suitable for use in pasteurization processes, including processes that require up to 85 ºC. It has also been shown that the inclusion of aluminum foam in paraffin-based thermal energy storage devices increases the efficiency of heat transfer, which allows for rapid recharging and discharging of energy [118]. However, the use of energy stores that do not contain aluminum foam does not reduce the performance of the pasteurization system [119]. The challenge that can result from the need for high initial financial investment persists for this project.

2.2. SODIS systems for water treatment

Vidal and Díaz [120] built a continuous flow (with recirculation) solar water disinfection system. The system consisted of 12 tubular Pyrex reactors, fixed in the focus of CPC collectors, and had 4.5 m^2 of total collection area. Raw water (total volume 25 L, turbidity 0.8 - 0.9 NTU) experimentally contaminated by *E. coli* and *Enterococcus faecalis* (~10^3 CFU/mL) was allowed to flow through the system. Inactivation of all bacteria to below detection level was reported by exposure to a total solar UV dose of 15 W-h/m^2 for *E. coli* and ~20 W-h/m^2 for *E. faecalis*. The authors estimate that the system produces 50 L/m^2 per hour.

Beattie et al. [121] evaluated the effectiveness of two different approaches to solar disinfection by UV radiation in inactivating bacteria present in water. The experiment consisted of placing water experimentally contaminated by *E. coli* (10^5 CFU/mL) in quartz tubular reactors, fixed in the focus of parabolic collectors or on flat collectors. The reactors fixed in these two types of collectors were exposed to the sun for 2, 4, and 6 h. It was observed that total inactivation of *E. coli* in the water contained in the reactors coupled to the two types of collectors occurred after 2 hours of sun exposure. Bacterial inactivation rates in different types of collectors were not significantly different. However, the water temperature increased significantly in the reactor fixed in the parabolic collector (~ 26 ºC) than in the reactor placed in the flat collector (~ 10 ºC), in relation to the initial water temperature. In the same year, a similar study involving three different SODIS approaches was published by Aboushi et al. [122]. These authors fixed three sets of borosilicate glass flasks at a height of 25 cm from the ground, after being filled with water experimentally contaminated with total coliforms, *E. coli* and *Pseudomonas aeruginosa* at a density of about 3 x 10^3, 5 x 10^2 and 2 x 10^2 MPN/100 mL, respectively. Mirrors were placed on the floor below two sets of bottles; for one group a flat mirror and for another, a parabolic mirror was placed. The rates of bacterial viability reduction after 150 min of exposure in each disinfection approach, in descending order of effectiveness, were: flat a mirror (96.8%, 99.6%, 96%), parabolic mirror (96%, 99) , 2%, 95%) and without mirror (95.9%, 97.2%, 90%) for total coliforms, *E. coli,* and *P. aeruginosa*, respectively. As in the study by Beattie et al. [121] the results of this study suggest an insignificant difference between the disinfection efficiencies using flat and parabolic mirrors, as well as between these approaches and the approach without the use of mirrors.

McLoughlin et al. [123] built and tested three continuous-flow (recirculating) solar water disinfection systems based on solar collectors of three different shapes, on a laboratory scale. The systems consisted of six tubular reactors (250 mm long) made of borosilicate placed in the openings of CPC, PTC, and V-groove (Fig. 11A). In the V-groove (angle 45°), the center of the tube was positioned 14 mm above the base. The total areas of collection of the systems were 0.057 m^2, 0.042 m^2 and 0.057 m^2, for systems with CPC, PTC and V-groove collectors, respectively. The system was tested to disinfect water contaminated with *E. coli* K-12 (10^6 CFU/mL), at a flow rate of 2.8 L/min, and exposed to sunlight for up to 60 min. During the tests, the water temperature did not exceed 38 ºC. While a ~3 log reduction in bacterial viability was obtained in systems with PTC and V-groove collectors, in the system based on CPC collectors, a >4 log reduction was achieved. Later, other authors built two similar solar water disinfection systems, which were tested to treat water collected from rain, in batch or continuous flow disinfection processes with recirculation [45]. One of the systems was based on CPC collectors with a concentration factor of 1.04 and 6 tubular reactors, with a collection area of 2.04 m^2 and a capacity of 32 L (30 L of illuminated volume). The other system was based on V-groove collectors with a concentration factor of 0.56 and 10 tubular reactors, measuring 1.98 m^2 of the collection area and having a capacity of 54 L (illuminated volume of 50 L). The reactors were made of borosilicate (with 89-90% UVA transmittance) and were fixed in the focus of each collector (Fig. 11B). The authors tested and compared the effectiveness and productivity of these systems in eliminating bacteria (*P. aeruginosa*, *Salmonella enteriditis*, *E. coli* and *Enterococcus faecalis*). A >5 log reduction in bacterial viability for *P. aeruginosa*, *S. enteritidis*, *E. coli* and *E. faecalis* (in order of susceptibility) has been reported during an exposure time between 40 and 90 min, corresponding to a dose of UVA between 130 and 250 kJ/m^2. Similar efficiency in bacterial inactivation in water has been reported in V-groove systems and CPC collectors. However, the system based on the V-groove collector can treat 162 L daily and the CPC 96 L, per module with 2 m^2 of collection area (corresponding to 3 lots), on sunny days with at least 300 min of clear sun. In batch disinfection, bacterial inactivation (with >5 log reduction) was achieved in less exposure time than when the continuous flow (with circulation) disinfection approach was used in both systems. Exposure times of 90 and 300 min for *E. coli* and 120 and 300 min for *E. faecalis* were required to achieve inactivation of >5 log in water, using batch disinfection and continuous flow disinfection approach with recirculation, respectively.

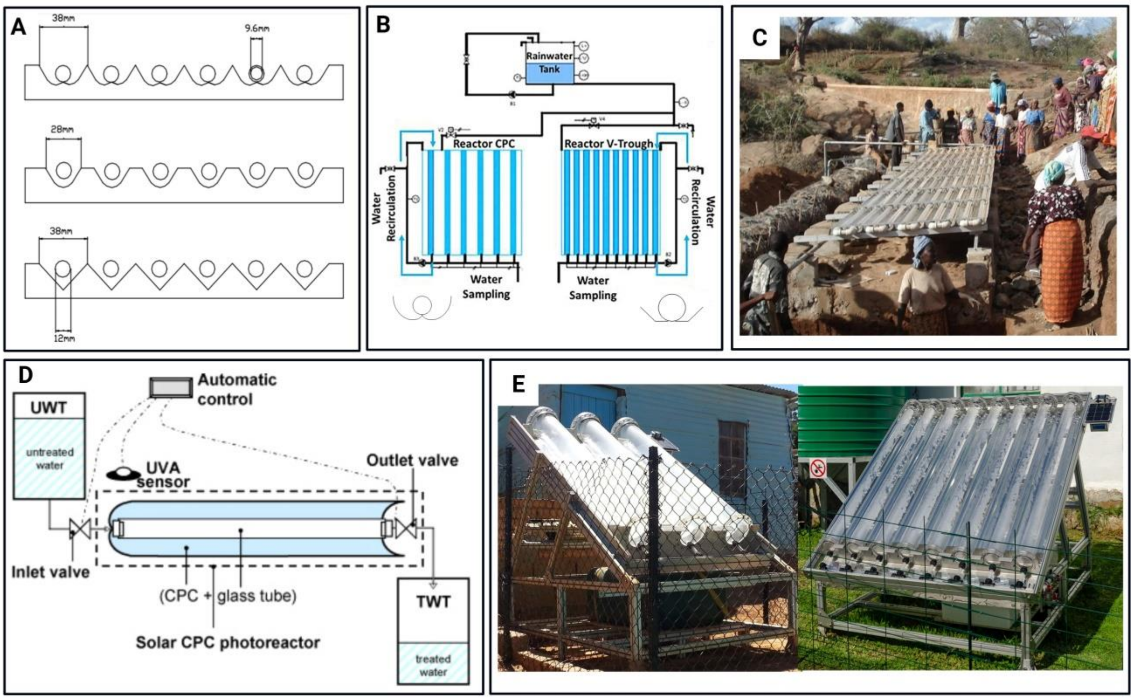

Fig. 11. Main configurations of solar water disinfection systems based on ultraviolet radiation (SODIS). (A) Different configurations of solar concentrators tested in SODIS systems ([123] License: 5163200219599). (B) SODIS system for continuous flow solar disinfection, with water recirculation, based on compound parabolic concentrators (CPC) and V-groove concentrators ([45] https://creativecommons.org/licenses/by/4.0/). (C) SODIS continuous flow solar disinfection system, based on CPC collectors, being installed in a village in Kenya with the help of the local community ([40] License: 5163200992605). (D) Autonomous solar disinfection system in sequential batch ([67] License:

5163211100704). (E) Batch solar water disinfection reactors with a capacity of 140 L (left) and 88 L (right) ([32] License: 5280400390066).

Ubomba-Jaswa et al. [124] evaluated the effect of solar UVA radiation dose on the inactivation of *E. coli* K-12 present in well water (~10^6 CFU/mL) contained in different tubular borosilicate reactors, fixed in the focus of CPC collectors. The effects of water temperature, volume (2.5 - 10 L), flow rate and disinfection approach (batch or recirculation with intermittent exposure) were also evaluated. Complete water disinfection, with reduction of bacterial viability to below the detection limit, has been reported by uninterrupted exposure (batch) to a minimum total dose of UV radiation >108 kJ/m^2. It was established that the higher the UV dose, the shorter the exposure time needed to achieve 100% bacterial inactivation. When water was disinfected using a continuous flow disinfection system with recirculation, complete inactivation was not achieved even after 5 h of exposure to strong sunlight and a cumulative dose of >108 kJ/m^2. On the other hand, when the water was kept for more than 5 h at a temperature of 45 and 55 ºC, complete bacterial inactivation was also achieved. These results strengthen the notion of the synergistic effect of heat (>45 °C) and solar UV on the effectiveness and acceleration of water disinfection during SODIS.

Gill and Price [40] installed a continuous-flow solar water disinfection system, to treat surface water from a dam in a Kenyan village for potable use. The system consisted of tubular pyrex reactors measuring 47.2 mm in diameter placed in the focus of compound parabolic concentrators (CPC), measuring 120 m in total reactor length (Fig. 11C). The tests were carried out with the system adjusted to a flow of 10 L / min, so that the water took 20 min to travel the entire length of the reactor. Subsequently (three years later) it was reported that extreme droughts and floods, as well as sociocultural, economic and technical challenges, hampered the use and performance of the system [125].

Polo-López et al. [67] developed and tested an autonomous sequential batch solar water disinfection system based on a CPC collector (with a concentration factor of 1.89) containing a tubular borosilicate reactor (89-90% UVA transmittance) with capacity 2.5 L of illuminated volume, placed in its focus. The input and output of raw water from the reactor were controlled by electronic valves, regulated by software that used incident UVA radiation data, provided by a photodiode (Fig. 11D). After the water was exposed to a pre-programmed dose of UVA, the outlet valve opened to release the disinfected water and then closed. Once the reactor was empty, the inlet valve opened to fill the reactor with raw water. Reduction of bacterial viability to below the detection limit in well water experimentally contaminated with *E. coli* K-12 (10^6 CFU/mL) was achieved by exposure to a cumulative dose of 245 kJ/m^2 (corresponding to 60 min sun exposure) with instantaneous decay of viability bacterial. Exposure to a cumulative dose of 180 - 229 kJ/m^2 (corresponding to 15 min of sun exposure) resulted in a gradual reduction in bacterial viability, which continued after discontinuation of sun exposure (Fig. 11D). The inactivation of 6 log of *E. coli* and the production of 15 L (corresponding to 6 batches) of disinfected water per day have been reported.

Reyneke et al. [32] built and tested two prototype large-volume solar reactors for batch disinfection. Reactor 1 had a total volume of 140 L and consisted of three interconnected tubes made of UV-A transparent polymethylmethacrylate, measuring 200 mm in diameter, fixed in the center of a V-shaped solar concentrator made of anodized aluminum. Reactor 2 was similar to reactor 1, differing in that it had 8 interconnected tubes of 100 mm in diameter and a total capacity of 88 L (Fig. 11E). The reactors were positioned at a 34º angle and installed in two communities in South Africa to treat the rain harvested water, by exposing it to the sun for 8 hours. On the sampling days, UV-A and UV-B radiation showed average values ranging from 7.164.63 W/m^2 to 31.29 W/m^2, and 1.334.63 W/m^2 to 4.63 W/m^2 respectively. *Escherichia coli*, total (3-4 log) and fecal (3-4 log) coliforms, enterococci (3 log), heterotrophic bacteria (4-5 log), *Klebsiella* spp. (2-4 log) and *Salmonella* spp. (3 log) were detected in 61%, 100%, 45%, 24%, 100%, 58.5% and 33% of the raw water samples analyzed, respectively. Reduction of bacterial viability in treated water below the detection limit in both reactors was reported for *Escherichia coli*, fecal coliforms, enterococci, *Klebsiella* spp and *Salmonella* spp. The mean reduction in the viability of total coliforms and heterotrophic bacteria was 33 and 50% in reactor 1 and, 89 and 14% in reactor 2. The water treated by these reactors was not considered safe for human consumption, based on WHO's guidelines [2].

Strauss et al. [125] built and tested a solar water disinfection device based on a CPC collector containing in its focus a single tubular reactor made of transparent borosilicate. The device was used to disinfect previously filtered harvested rainwater, as well as unprefiltered water, by exposing a 10 L batch to solar radiation for 8 hours. The rates of reduction in viability of *E. coli* and total coliforms (2 log per mL) were 99.9% and 97.3 - 99.9%, respectively. Bacterial inactivation rates in tests with pre-filtered and non-pre-filtered water were similar. An average rate of 99.5% reduction in viable *Legionella* copy number was obtained when a maximum UVA fluence of 29.5 W/m^2 was recorded in the environment. An average reduction of 99.8% for *Pseudomonas* was achieved when an average maximum UV-A environmental fluence of 20.5 W/m^2 and a temperature ≥ 52 °C in the treatment water were recorded. In some sampling sessions, although a substantial reduction in bacterial viability was achieved, a residual bacterial viability was observed.

Cisterna-Osorio et al. [127] developed a solar wastewater disinfection system to be reused in agriculture. It is a channel with trapezoidal geometry (measuring 2.0 x 0.5 x 0.43 m) covered with reflective material that reflects the radiation into the water contained in the channel. Solar radiation that is reflected out of the channel is reflected back into the channel by mirrored panels placed at specific angles to the channel opening. When the batch of water contained in the channel was exposed to solar radiation for 150 min, a reduction in bacterial viability of up to 99% (10^3 NMP/mL) was reported for total coliforms.

2.2.1. How to improve disinfection systems based on solar ultraviolet radiation?

All solar water disinfection systems by UV radiation, with the potential to be applied to the large-scale public drinking water supply, described here, are based on concentrator-type solar collectors [40,45,67,120,126]. Most of the concentrators used are of the CPC type, although PTC, V-slot, parabolic plate and trapezoidal geometry collectors have also been used [126,127,128]. It has been suggested that the effectiveness of UV solar disinfection systems is more determined by the UVA and UVB transmittance of the material with which the reactor used was made [129] than by the use or not of the collector solar.

However, the acceleration of microbial inactivation by the contribution of heat is greatest when a concentrating collector is used [121,122]. Contrary to these two studies, it was reported that placing a reactor at the focus of a concentrator collector in a parabolic basin with a reflective surface increased by 21-28% the photolysis rate of the drug (ciprofloxacin) in water by solar UV radiation [128]. Reactors made of quartz, borosilicate, polypropylene, polymethylmethacrylate, pyrex (with low iron content) and methacrylate have been shown to be more suitable for solar water disinfection processes based on UV radiation [129,130,131].

As for the shape of the concentrator, two studies showed slightly contrasting results [123,131]. In the study by McLoughlin et al. [123] it was reported that in the system based on CPC collectors a higher efficiency was obtained (with a reduction in bacterial viability of >4 log FUC/mL) than in the system based on PTC and V-groove collectors (with a reduction in viability of ~3 log FUC/mL). However, in the study by Martínez-García et al. [45] a similar performance in terms of microbial inactivation efficacy was reported between CPC-based systems and V-grooved collectors, however, a higher daily potable water productivity was obtained in the system based on V-grooved collectors (productivity 81 L/m^2 per day) than in the system based on CPC collectors (productivity 48 L/m^2 per day). This higher productivity reported for the system based on V-groove collectors was attributed to the fact that this configuration allows a better use of space, since more reactors can be used in this system (5 reactors per m^2) than in the CPC-based system collectors (3 reactors per m^2). The batch disinfection approach has been consistently shown to be more effective at microbial inactivation than recirculating flow disinfection approaches [45,124]. This means that sequential batch or continuous flow disinfection should be the most preferred approach; however, it is necessary to ensure that the water is continuously exposed to an adequate minimum dose of UV radiation to achieve safe microbial inactivation. The findings by Polo-López et al. [67] suggest that exposure to a minimal dose of ultraviolet radiation (245 kJ/m^2), even for a short exposure time, triggers severe cell damage that leads to complete bacterial inactivation and, although inactivation is not immediate, the impairment of cell viability continues in the dark. This means that the productivity of solar disinfection systems based on UV radiation can be increased by increasing the dose of UV radiation directed to the reactor, which can be achieved by increasing the concentrator opening (especially CPC, improved by Jadhav et al. [103]. The use of the panel developed and tested by Lee et al. [41] as a reactor, if built with materials with high transmittance to solar UV radiation, could improve the performance of UV disinfection systems. However, in this case, it will be necessary that the channels are interconnected in a serpentine to increase the water's solar exposure time.

The solar water disinfection system installed by Gill and Price [40] in Kenya is one of the highest flow rate UV radiation disinfection systems that have been installed for drinking water supply in a real-life situation. The use of a CPC collector, enhanced by truncation to obtain greater opening of the collector without significant increase in height [103] can increase the performance and productivity of this system. Furthermore, the integration of a filtration step prior to disinfection would ensure the removal or reduction of turbidity [132] and thus increase the chance of complete microbial inactivation in the water. Slow filters (biosand filters) may be a suitable technological option, as their effectiveness in removing turbidity and considerably reducing the microbial load of water has been documented [133,134,135]. In addition, they are affordable, cheap and easy to install; they suit scenarios where logistical, financial and technical challenges can hamper the success of solar water disinfection systems.

2.3. SOPAS + SODIS systems for water treatment

Rijal and Fujioka [49] evaluated the effectiveness of combining the effects of optical and thermal radiation from the sun on water disinfection, using a solar disinfection system based on a flat plate solar collector. The system built was a box made of high-density black polyethylene, resistant to high temperatures, measuring 51 × 122 × 8 cm^3 in width, length and height, respectively. The collecting face was covered with a layer of UV-transparent acrylic and a second layer of thin plastic, equally permeable to UV radiation. Another control device was built; however, this received, in addition to an acrylic cover, a UV-impermeable double-layer plastic. During testing, a batch (~19 L) of water mixed with sewage water (with 1.4 - 2.5 NTU) was placed in each device which was then exposed to the sun for up to 5 hours. Water disinfection, with a

> 3 log (99.9%) reduction in the viability of fecal coliforms and *E. coli*, during 2 to 5 h of sun exposure, at a temperature of 60 °C, has been reported in both devices. However, only in the device with a face permeable to UV rays, the same result was achieved even when the water temperature did not reach 60 °C; this result was attributed to the synergy of UV and solar thermal energy.

Thimmannabhat et al. [136] developed a continuous flow solar water disinfection system using the combined effect of heat and UV radiation. In this system, water is heated to temperatures > 40 °C and then flows through a solar UV disinfection reactor. The heater and the UV disinfection reactor are flat collectors, and on their sides flat mirrors were placed at appropriate angles (60º) to concentrate the solar radiation on the surface of the collectors. The heater is a box measuring 75 x 53.5 cm^2 in area and a width of 28 mm. The wall facing the sun is of double glass, and inside the box is placed a tubular coil of stainless steel painted black. The water flows from the raw water tank, through the coil in the heater and then flows into the UV disinfection reactor at a flow rate of 330 mL/min. The UV radiation disinfection reactor has a structure similar to that of the heater, differing in that the wall facing the sun is made of simple glass permeable to UV radiation. And in place of the metallic tubular coil, there are narrow and shallow grooves through which preheated water flows, being irradiated by solar UV radiation. The system has been installed on a metal frame with wheels to facilitate intermittent manual adjustment (~1 time per hour) of the system to align it towards the sun. A productivity of 20 L/h of disinfected water (with 3 log bacterial inactivation) was reported when the intensity of solar radiation in the horizontal plane was 940 W/m^2, operating stably for 6 h per day.

Saitoh and El-Ghetany [50] built and tested a solar disinfection system that combined the effect of UV radiation and heat to inactivate microorganisms in water. The system is essentially a hot box solar cooker, made of wood measuring 0.6 m^2 of horizontal plane area, as well as 0.3 and 0.461 m in height of the front and back walls, respectively, so that the side walls had the trapeze shape. The inner faces of the side walls were lined with Styrofoam (0.05 m thick) and then coated with reflective aluminum foil. The basal wall was lined with aluminum sheet painted black (measuring 0.5 m^2 in area and 0.5 mm in thickness). The upper face of the box (with a 15º inclination in relation to the horizontal plane) was made of two layers of double glass with a spacing of 0.04

m between them, to avoid thermal losses (there are no details on the nature of the material with which glass was made, but is assumed to be permeable to UV radiation). A reflector (measuring 0.62 × 0.60 m^2 in area) was attached to the rear hood of the thermal box to collect the radiation and reflect it on the top (glass) face of the box. Inside the thermal box, in the center of the basal surface, a cube-shaped reactor (measuring 0.2 m^3), made of Pyrex glass, was placed. The water mixed with sewage was made to flow from the raw water tank (100 L), passing through a filter (5 μm) and then through a heat exchanger where it was preheated. The preheated water then flowed to the reactor where it remained until reaching the temperature of 65°C that was programmed in the thermostatic solenoid valve. The disinfected water then flowed into the biologically clean water storage tank passing through the heat exchanger. Although a ~2.5 log per mL (50%) reduction in coliform viability was observed after 1 h of exposure (volume 2-5 L), reduction of bacterial viability to below the detection limit (with >5 log inactivation) was achieved after 3 h of exposure time. However, in another device, where a black painted copper tube was used as a heat absorber attached to the focus of a compound parabolic concentrator, complete disinfection under the same test conditions was achieved within 30 min.

Dayem et al. [137] tested four different configurations of tubular reactors, placed in the focus of PTC collectors (measuring 2 m^2 of collection area) to measure their effectiveness in solar disinfection of water contaminated by bacteria. The first reactor (optical-thermal) was a stainless steel tube painted black and placed inside a Pyrex glass tube. The water was made to flow in the space between the Pyrex casing and the stainless steel tube. The second reactor (thermal) was similar to the first, but water flowed through the inner space of the stainless steel tube. The third (optical) reactor consisted of a Pyrex glass tube, and water flowed through it. The fourth reactor consisted of a combination of the two types (optical and thermal), the water flowing from the optical reactor (third reactor) and then through the thermal reactor (second reactor) (Fig. 12A). The system was operated at a flow rate of 4.5 L/min. Although microbial inactivation was observed in all reactors, the approach that combined the thermal and optical reactor (fourth reactor) proved to be more effective in microbial inactivation. Furthermore, mixed disinfection in the heat +

UV sequence was shown to be slightly more effective than the heat UV sequence. It was also observed that the higher the water temperatures, the higher the microbial inactivation rate. A reduction in bacterial viability (total coliforms and spore-forming bacteria) of 99.4% (from an initial density of 10^5 NMP/100mL) has been reported. A daily production of 582 L of pasteurized water was estimated for every 2 m^2 of collection area under Cairo's climatic conditions.

Monteagudo et al. [42] built a sequential batch solar system for water treatment, combining the optical and thermal effects of the sun. The system consisted of a raw water tank (50 L), a photoreactor based on CPC collectors (area = 0.25 m^2, volume = 1.01 L), a heat exchanger and a solar pasteurization system (area = 0 .5 m^2, volume = 0.5 L). In the focus of the CPC collectors, tubular reactors of borosilicate glass were placed. The reactors were made of two concentric tubes and the outer surface of the inner tube was coated with TiO_2 (Fig. 12B). Raw water flowed through the optical reactors and then through the pasteurizer. 99.6% inactivations of *E. coli* (2 x 10^6 CFU/mL) as well as 30 - 70% degradation of pharmaceutical antipyrine (5 mg/L) were achieved in the optical reactor, during 80 min of exposure. Complete inactivation of *E. coli* remaining in the water was reported during passage through the pasteurizer, equipped with a thermostatic valve at the reactor outlet, programmed to open at a temperature of 80 ºC.

Chaúque et al. [117] built and tested a continuous flow solar water disinfection system that uses the effect of optical and thermal energy, and consisted of two main modules. The first module was a heater based on a PTC collector (measuring 3.0 x 1.0 m^2 of collection area) with an aluminum double tube absorber (painted matte black) placed in its focus. The second module consisted of a fresnel-type primary concentrator (measuring 4.5 x 1.0 m^2 of collection area), which directs the collected radiation to the opening of a secondary collector, which is a placed PTC collector (Fig. 12C). In the opening of the secondary collector, tubular quartz glass reactors were placed, and one of these reactors was in the focus of this collector (Fig. 12D). During the disinfection process, the water leaves the raw water reservoir, passes through the heat absorber (in the heater) where it heats up, then the hot water flows through the quartz reactors, where it is radiated by collimated beams of solar

UV radiation. Reduction of bacterial viability to below the detection limit in water simultaneously contaminated by >10^5 CFU/mL of each of the bacteria (*E. coli*, *Salmonella Typhimurium*, *Enterococcus faecalis* and *P. aeruginosa*) was achieved by UV exposure for 0.5 min at a temperature of 55 °C or 60 °C for water with <1 NTU or 50 NTU, respectively. Reduction of protozoan viability to below the detection limit in water contaminated by *Acanthamoeba castellanii* cysts (10^8 cysts/L) was also achieved by the combination of heat (60 °C) and UV exposure for 0.5 min or 10 min to water with <1 NTU or 50 NTU, respectively. Considering *A. castellanii* cysts as a model and water with 50 NTU, average daily production of 360 L was reported.

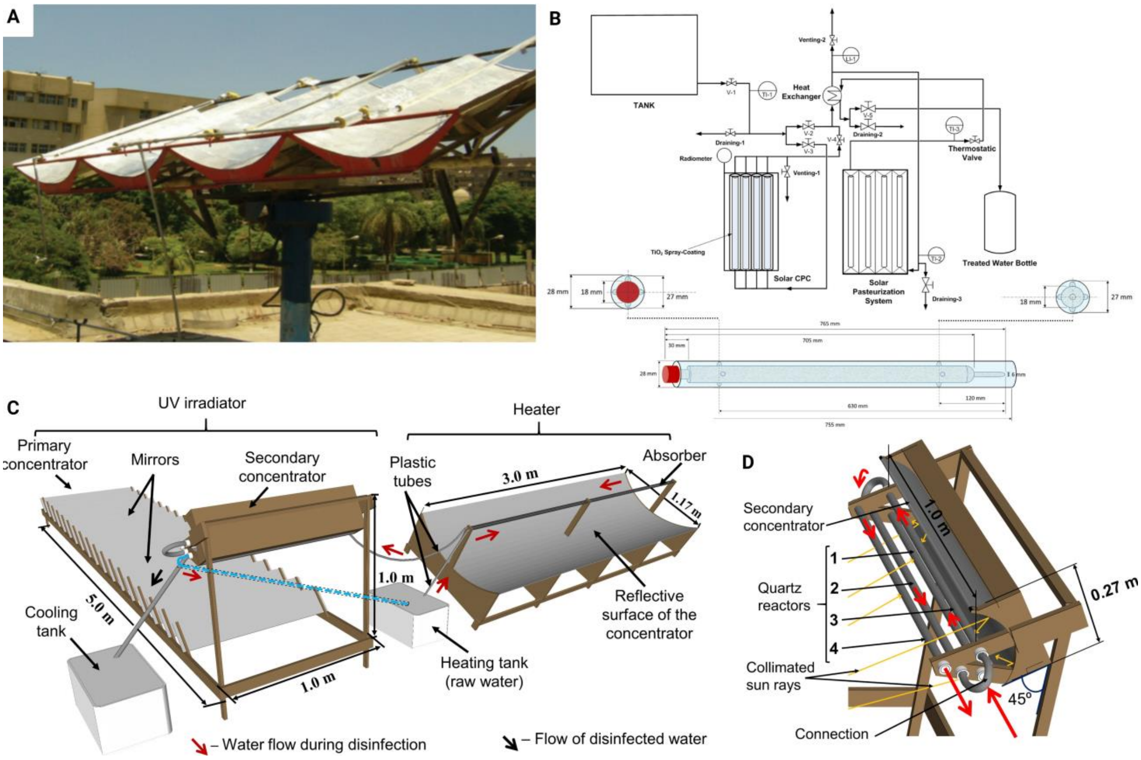

Fig. 12. Solar water disinfection systems based on the synergy of thermal and optical energy from the sun (SOPAS + SODIS). (A) SOPAS + SODIS disinfection system for continuous flow water based on PTC collectors [137]. (B) System configuration based on SOPAS + SODIS + photocatalysis (TiO_2) for sequential batch disinfection and elimination of drugs from water ([42], License: 5163221281473). (C and D) Overview of the SOPAS + SODIS system and details of the secondary ([117] License: 5163230220771).

2.3.1. How to improve SOPAS + SODIS systems?

Solar disinfection systems that combine the effects of heat and UV radiation have a lower chance of microbial inactivation failure than systems based on just one of the mechanisms [33,35,47,137]. Furthermore, it seems obvious that these systems have greater stability of efficiency and productivity during most of the daylight hours, since the minimum acceptable values of temperature and radiation are sufficient to achieve a high performance in microbial inactivation.

The mixed solar water disinfection systems described in the literature are essentially based on concentrators, although non-concentrating collectors are also used. The improvements presented above for pasteurization systems as well as for UV disinfection systems are generally applicable to mixed systems. An interesting improvement was made by several authors [138,139,140,141], these inventors proposed the installation of UV germicidal lamps (UVA, B and C) inside the heating tank of solar pasteurization systems, including pasteurisers based on flat plate or vacuum tube collectors, similar to the systems tested by Kang et al. [51] and Dobrowsky et al. [58]. The installed lamps are powered by electricity generated by a photovoltaic panel. For that, the use of UV-LED lamps can be the best option, as they demand less energy. However, UVC radiation needs to be the first option as high rates (7 and 4 log) of bacterial inactivation (*E. coli* and *Klebsiella pneumoniaii*) have been reported by exposure to a UVC dose of 21.5 mJ/cm^2. On the other hand, it was reported that the effectiveness of the combination of UVC (265 nm) and UVA (365 nm) did not show a positive synergistic effect [142]. The current high costs of LED UVC lamps, although their cost is constantly decreasing over time, can pose a challenge to the accessibility of solar disinfection systems that integrate this technology. An interesting innovation was also developed by Yun [143] who developed a mixed solar disinfection system to treat drinking water. The system is essentially a solar heater based on evacuated tube solar collectors with special properties. Solar collectors consist of an outer tube and an inner tube. The outer tube transmits solar ultraviolet radiation. The inner tubes have a heat absorbing part and a UV transmitting part. The solar UV transmitting part is facing up. These characteristics allow the microorganisms present in the water to be exposed to heat and, when present in the water contained in the absorbers, they are also exposed to solar UV radiation.

The development of mixed solar disinfection systems based on flat solar collectors that laterally concentrate and condense solar radiation has the potential to result in high performance water treatment systems. In these collectors, solar radiation that passes through a transparent glass wall (with a flat or concave surface) is concentrated in flat mirrors that, in turn, deflect the radiation to a channel with walls with reflective surfaces. In this channel, radiation is condensed as it is directed to the surface of a reactor [107,108,109] (Fig. S6). This reactor can contain thermal energy absorption regions (to heat water) and UV transmittance regions, similar to the one developed by Yun [143].

In general, the SOPAS and SODIS systems discussed above can be combined after being improved to develop high-performance mixed systems applicable to large-scale water supply. Depending on the scale and configuration of the mixed system to be built, it is advisable that the SOPAS and SODIS parts be built on the same support structure, especially if the system is designed to track solar radiation in two axes.

2.4. How is the productivity of the different types of solar water disinfection systems?

The data (Table 1) suggest that the mean productivity value of SOPAS systems is more influenced by the type of solar collector used than by the disinfection approach adopted. The data also show that the average productivity of drinking water is higher in systems based on evacuated tube solar collectors (124.8 ± 64 L) than in those based on flat plate solar collectors (41.5 ± 21 L). Pearson's correlation tests (Table S3) show that water productivity in SOPAS systems is strongly negatively correlated with initial microbial density in raw water (-0.55) and water temperature (-0.59), and positively correlated with intensity of solar radiation (0.60) ($p > 0.5$). These findings make sense, as they show that the higher the microbial density in raw water and the disinfection temperature chosen, the lower the volume of potable water processed per time. The results also show that the greater the intensity of solar radiation, the greater the volume of water produced.

Table 1. Profile and productivity of solar water pasteurization systems per 1 m^2 of collection area.

Collector type	**Disinfection approach**	**Initial microbial density** (log/mL)	**Solar irradiation** (W/m^2)	**Water temp.** (^{o}C)	**Daily water productivity** (L)	**Ref.**
Flat plate*	Batch	5 - 7 [a]	ni	62 ± 6.1	62.5	[51]
	Sequential batch	ni	800	60	73.1	[52]
		ni	800	90	16.7	
	Sequential batch	1 - 3 [a,b]	300	85	15	[53]
	Sequential batch	1 - 4 [c,d]	261	85	40	[54]
Evacuated tube*	Batch	1 - 2 [a,e]	1000	72 ± 2	72	[58]
	Batch	< 1 [a,b,e,c]	1000	≥ 66	80.2	[59]
	Convection circuit	ni	955	~ 78	222.2	[61]
PTC **	Sequential batch	9 [a]	850	87	11.6	[82]
Parabolic solar disk **	Continuous flow	6 [a]	150	58 - 65	27.9	[43]

Solar tracking: (*) - Stationary; (**) – 1 axis tracking. PTC - parabolic trough concentrators. ni – Not informed. Target microorganism tested: (a) *E. coli*; (b) - Total coliforms; (c) - heterotrophic bacteria; (d) - *Pseudomonas aeruginosa*; (e) - fecal coliforms.

All SODIS systems whose data were used in the analysis are based on concentrator-type solar collectors (Table 2). In general, the literature suggests that drinking water productivity is higher in SODIS systems using a recirculating or continuous flow disinfection approach. The results of the Pearson correlation test (Table S4) suggest that the productivity of drinking water in these systems is strongly negatively correlated with the log of inactivated microorganisms in the water (-0.52). In turn, the log of inactivated microorganisms in the water is positively correlated with the cumulative dose of available UV radiation ($p > 0.5$). These results make sense, as they indicate that the higher the density of microorganisms removed, the lower the volume of drinking water available, and the higher the microbial density, the greater the amount of solar radiation required to reduce microbial viability to values below detection limit.

The data (Table 3) suggest that SOPAS + SODIS systems based on concentrator-type solar collectors are more productive than those based on non-concentrating solar collectors. Likewise, the continuous flow disinfection approach is more productive than the batch or sequential batch disinfection approach.

Table 2. Profile and productivity of water disinfection systems by solar ultraviolet radiation per 1 m^2 of collection area.

Collector type	**Disinfection approach**	**Cumulative UV solar radiation** (W/m^2)	**Residence time** (min)	**Daily water productivity** (L)	**Log removal** (log/mL)	**Ref.**
CPC	Recirculation	27 – 54 x10^3	30	133,3	3 [a,d]	[120]
CPC	Continuous flow	≥ 30 x 10^3	20	444	2 [b]	[40]
CPC	Sequential batch	245 x 10^3	15	34	6 [a]	[67]
CPC	Batch	14,2 x 10^3	8	23	< 2 [a,b,c]	[126]
V-groove collector	Batch	130 x 10^3	90	81	5 [a,c,d]	[45]
	Recirculation	250 x 10^3	300	81	5 [a,c,d]	

CPC - compound parabolic concentrators. Target microorganism tested: (a) *E. coli*; (b) Total coliforms; (c) *Pseudomonas* spp.; (d) *Enterococcus faecalis*.

The productivity values of the most productive SOPAS + SODIS systems are not directly comparable, as one study used bacteria [136] and another used protozoan cysts (which are more resistant to heat and UV than bacterial cells) [117]. However, the fact that cyst inactivation was achieved in a continuous flow solar disinfection system confirms that SOPAS+SODIS systems are also effective against environmentally resistant forms of protozoa. The results of Pearson's correlation test (Table S5) indicate that drinking water productivity in SOPAS + SODIS systems has a strong positive correlation with water temperature (0.86) and a strong negative correlation with water residence time (-0.66). Although the correlation between water productivity and UV fluence is also positive, it is weak (0.13) ($p > 0.5$). Although these results suggest that the contribution of heat to microbial inactivation is greater than the contribution of UV, they also suggest that further improvements in the mechanisms of collection and use of solar UV radiation are still needed.

In developing improved SOPAS + SODIS systems, it is necessary not only to look for the effective combination of SOPAS and SODIS devices, but to combine different SOPAS devices as well as various SODIS configurations. For example, evacuated tube solar collectors (which have been shown to be more effective) can be combined with Fresnel, or parabolic, collectors to improve SOPAS device performance in SOPAS + SODIS systems.

Table 3. Profile and productivity of solar water disinfection systems that combine the effect of heat and ultraviolet radiation (SOPAS + SODIS) per 1 m^2 of collection area.

Collector type	**Disinfection approach**	**UV fluency** (W/m^2)	**Water temp.** (°C)	**Residence time** (min)	**Daily water productivity** (L)	**Microbial density** (log/mL)	**Ref.**
Flat plate*	Batch	ni	40-56	120 - 150	30	1 [a,c,e,g]	[49]
Solar hot box + flat mirror**	Sequential batch	~ 900	65	90	16	> 3 [b]	[50]
PTC**	Continuous flow	~ 700	65-79	1	291	3 [b,h]	[136]
PTC + Fresnel***	Continuous flow	150 - 250	60	10 ± 0.5	48	6 [a,d,f,i,j]	[117]

Solar tracking: (*) Stationary; (**) 1 axis tracking, (***) 2 axis tracking. PTC - parabolic trough concentrators. CPC - compound parabolic concentrators. ni – Not informed. Target microorganism tested: (a) *E. coli*; (b) Total coliforms; (c) Heterotrophic bacteria; (d) *Pseudomonas aeruginosa*; (e) fecal coliforms; (f) *Enterococcus faecalis*; (g) enterococci; (h) spore-forming bacteria; (i) *Acanthamoeba castellanii* cysts; (j) *Salmonella* Typhimurium.

A direct comparison between the productivity of drinking water by these three types of systems does not provide relevant information, as they are very heterogeneous. However, the data (Tables 1, 2 and 3) as well as the results of the correlation test suggest that the productivity of drinking water is influenced by the type of collector, disinfection approach, intensity of solar irradiation, density of target microorganisms, and, mainly due to system configuration. The data also suggest that SOPAS + SODIS systems are more effective in microbial inactivation, and that continuous flow or intermittent flow disinfection approaches in systems based on concentrating solar collectors or evacuated tubes are more productive.

3. Conclusions

Although batch solar disinfection systems with high daily water productivity are reported, the systems with the greatest chance of producing large volumes of drinking water are those that disinfect water by sequential batch and continuous flow approaches. All solar water disinfection systems reviewed in this work can be improved, and thus improve their performance. The integration or improvement of the solar concentration capacity, as well as the improvement of the efficiency of the absorbers and/or reactors, stand out among the most important improvements that need to be made to substantially increase the productivity of the described systems.

Although the literature presents several SOPAS and SODIS systems that are very productive or with the potential to become highly productive if successfully improved, mixed systems (combining SOPAS and SODIS mechanisms) have greater potential to be more effective, more productive and more stable.

Overall, the results of the analysis of the productivity of each type of solar disinfection system clearly show that improvements in SOPAS systems need to focus on increasing the performance of collection, concentration and use of solar heat, as it is the most decisive variable in their productivity. In SODIS systems, the microbial density (or particulate matter suspended in the water) is decisive for the performance of the system; designers need to invest in increasing the performance of the device to collect, concentrate and direct UV radiation. The results seem to suggest that UV fluence is more important in drinking water productivity than microbial exposure time in SODIS systems. In SOPAS + SODIS systems, concentrator-type solar collectors are more desirable, and these systems need to be designed to operate in either continuous-flow or intermittent-flow disinfection approaches.

4. Recommendations for future work

Much has already been done in the field of research on water treatment technologies based on solar radiation and, thanks to this effort that has intensified over the years, there is none doubt about its effectiveness for the production of biologically safe drinking water and the potential of its use as an alternative supply of safe drinking water. Currently, there are several solar technologies applicable to drinking water treatment and some of them are commercially available in the form of solar energy-based devices. However, there is still progress to be made to enable solar drinking water treatment technologies to become robust solutions capable of positively impacting the accessibility of safe drinking water, especially among underserved populations around the world. For this, it is necessary to develop high-performance solar water disinfection systems, which can be applied in large-scale public drinking water supplies at low cost. These desired advances need to become targets of future research, and the following aspects should be considered:

- Improving the design and configurations of solar water disinfection systems currently described in the literature. These improvements need to focus on maximizing capture and efficiently using solar radiation to inactivate microorganisms (including resistant microorganisms) in the water.
- Development of new high-efficiency systems for capturing and directly or indirectly using infrared, ultraviolet and visible solar spectrum radiation.
- Development of system configurations that combine the use of optical and thermal energy from the sun (SOPAS + SODIS systems).
- In developing improved SOPAS + SODIS systems, it is necessary not only to look for the effective combination of SOPAS and SODIS devices, but to combine different SOPAS devices as well as various SODIS configurations.
- Whenever possible, the advances to be sought should aim at the development of systems that operate in continuous flow, integrating a filtration step prior to disinfection.
- The possibility of efficiently and safely integrating photothermal and photocatalytic nanomaterials in solar disinfection reactors needs to continue to be researched.
- The integration of disinfection technologies based on artificial UV radiation, powered by photovoltaic panels in solar drinking water disinfection systems is a promising path to be explored [144,145], as it can balance the fluctuation in the availability of desired doses of UV radiation, resulting from the momentary shading of the sun.
- It is highly desirable that future studies seek to design and build solar drinking water treatment systems on larger scales, and test these systems in situations as close to reality as possible.
- Although it is necessary that large-scale solar water disinfection systems are capable of eliminating bacteria, they must be equally effective in inactivating other microorganisms, including protozoa, fungi and viruses whose inactivation by SODIS has already been documented [36,146,147].

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CAPÍTULO V

Artigo intitulado “Epidemiological and Immunological Gains from Solar Water Disinfection: Fact or Wishful Thinking?” publicado na revista Tropical Medicine & International Health. https://doi.org/10.1111/tmi.13807. Parte da metodologia da revisão sistemática bem como parte dos dados são apresentados em Material Suplementar – APÊNDICE XII.

Epidemiological and Immunological Gains from Solar Water Disinfection (SODIS): A Fact or Wish?

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ABSTRACT

Objective: There is still no consensus on the impact of using solar disinfection (SODIS) to reduce the prevalence of waterborne gastrointestinal diseases. The reported reduction in diarrhea prevalence among SODIS users has been attributed to the consumption of water free of viable pathogens. However, it has also been suggested that ingestion of SODIS-inactivated pathogens may induce protective immunological changes that may also contribute to a reduction in the frequency of diarrhea. The present study aimed to critically review the epidemiological and immunological gains of using SODIS.

Methods: We critically reviewed 22 articles published in English, selected from 2,118 records systematically retrieved from the databases.

Results: All trials (except one) reported a significant reduction in diarrhea prevalence among children using SODIS, but some of the systematic reviews based on data from trials report contrary findings. All in vitro and in vivo assays indicate that SODIS-inactivated pathogenic bacteria have the potential to induce immunological alterations that may result in protective immunological effects. Studies with a low risk of bias are still awaited to confirm the ability of using SODIS to reduce the prevalence of diarrhea.

Conclusion: However, reducing the prevalence of diarrhea depends on the success of SODIS delivery strategies in inducing behavioral changes in communities that result in the production of SODIS-compliant outcomes. The results of trials reporting a reduction in the prevalence of diarrhea due to the use of SODIS seem to support the hypothesis of the contribution of the protective immunological effect against diarrhea in SODIS users.

KEYWORDS: SODIS, diarrhea prevalence, drinking water, immunity, immunogenicity.

INTRODUCTION

Water is imperative for the continuity of any form of life, including human life. In human settlements, however, water is also associated with people getting sick, in this case, when the water ingested is contaminated. Although waterborne diseases associated with the consumption of biologically unsafe water also occur in developed countries [1], the mortality rate from these diseases is incomparably higher in developing countries, especially in low-income countries. Currently, around 2 billion people do not have access to safe drinking water, and for this reason, around 800,000 people die annually from water-related diseases [2,3,4]. A large proportion of these people are concentrated in poor countries, especially in Southeast Asia (38%) and Africa (53%) [1]. In these countries, rates of access to drinking water provided through conventional drinking water treatment and distribution systems remain low [3]. In these contexts, shallow wells, rivers, lakes, and springs are the main sources of water, and often this water is heavily contaminated, mainly due to inadequate sanitation [5]. This situation is due to the fact that the installation and operation of conventional drinking water supply systems is expensive. Estimates show that a high financial investment (US $37.6 billion) needs to be made per year (for 15 years) to extend safe drinking water services to the population without access to safely managed water services in the world [6].

Alternatively, solar water disinfection (SODIS) is an effective, affordable, and inexpensive unconventional method of providing safe drinking water and is therefore recognized by the WHO [2]. The effectiveness of SODIS has been widely proven against all groups of microorganisms, including viruses, bacteria, fungi, and protozoa [7,8]. The inactivation of environmental resistance structures of microorganisms (spores, cysts, and oocysts) has also been well documented [9]. The effectiveness of SODIS has been reported in warm and temperate latitudes as well as in cold regions of the globe [10,11]. Daily productivity of drinking water through SODIS ranges from ~1.5 L per batch to several hundred liters per unit of water treatment system [12,13,14]. The lowest daily productivity of drinking water (~ 1.5 – 20 L) was reported, especially in conventional SODIS. Conventional SODIS consists of exposing batches of water in containers made of material that transmits UV radiation (e.g.

polyethylene terephthalate (PET), polypropylene, transparent polycarbonate, polymethylmethacrylate) to the sun for at least 6 hours on sunny days [12,15,16,17]. The use of reactors with a capacity of 88 L and 140 L has also been reported [14]. In general, reports of producing higher volumes of disinfected water are associated with the use of solar water disinfection devices or systems. The use of improved solar water disinfection systems gives SODIS the potential to be used for public drinking water supply on a large scale. For this, advances in the state of the art are still needed in the development of intermittent or continuous flow solar water treatment systems [18].

The effectiveness, low cost, accessibility, and simplicity of SODIS, combined with the possibility of being used in all regions of the planet, make SODIS one of the useful tools to fight waterborne diseases in underserved communities. Interventions to improve drinking water quality (including SODIS) at the household level have been shown to result in greater gains in combating diarrhea in endemic settlements compared with interventions at the source [19]. Evidence suggests that campaigns to promote SODIS in low-income settlements can reduce the prevalence of diarrhea by up to a third [20]. A comprehensive review that includes more recent findings on the epidemiological gains from using SODIS is needed. Epidemiological gains are often attributed to changes in the level of human exposure to waterborne pathogens as people consume water free of viable pathogens. However, the contribution of immunological gains from the consumption of SODIS disinfected water to reducing the prevalence of waterborne diseases has received little attention. Although the influence of SODIS on immunity against cholera has been discussed [21], a review of the immune gains resulting from drinking SODIS-treated water is still needed in light of recent studies. In the present study, the epidemiological and immunological gains of SODIS-based interventions to improve access to safe drinking water were critically reviewed based on articles systematically retrieved from databases, following PRISMA 2020 guidelines [22]. The article retrieval strategy is presented in figure 1 and in the supplementary material.

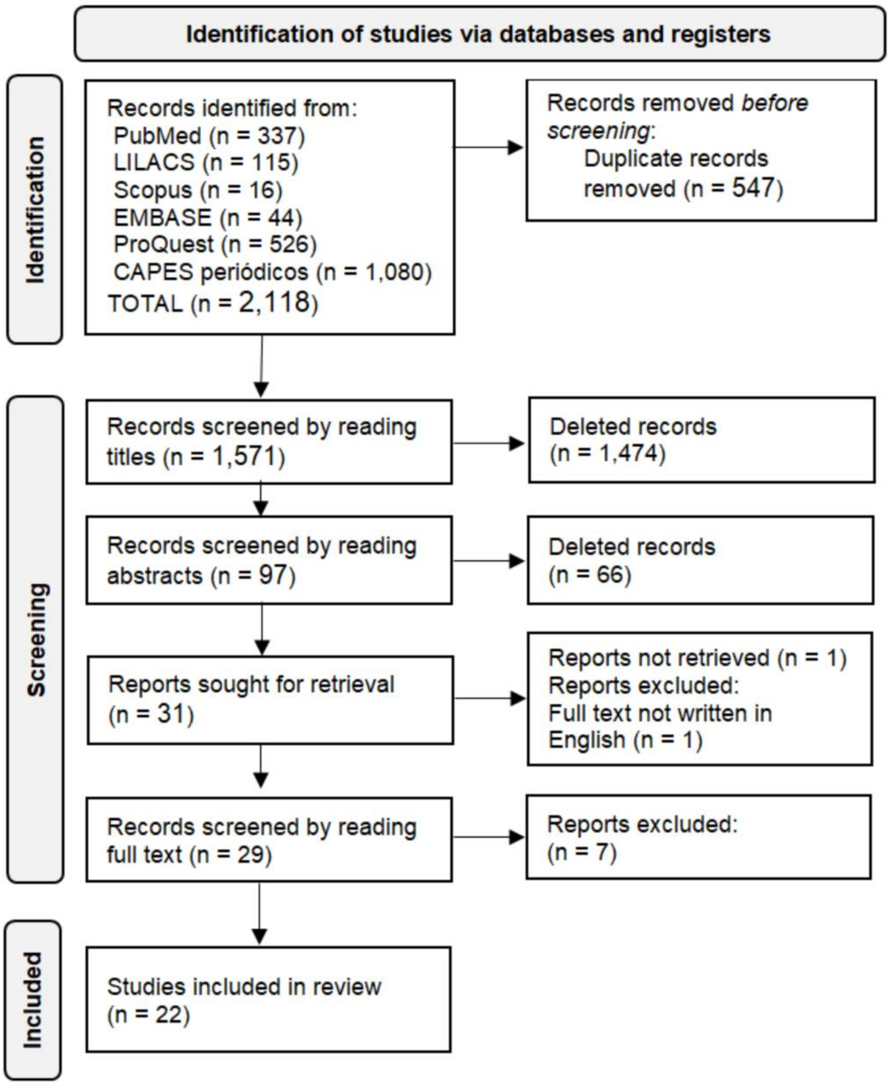

FIGURE 1 PRISMA flowchart of article retrieval and classification strategies.

Epidemiological gains from SODIS

Since the first report of SODIS [23] a wide range of studies have confirmed the effectiveness of SODIS against microorganisms of all taxa [7,24,25], so it is considered a suitable alternative method for providing safe drinking water. SODIS aroused and continues to arouse a lot of interest, not only for its effectiveness, but also for its accessibility and applicability in emergencies and contexts of needy and low-income communities. However, despite the effectiveness of SODIS having been robustly established, the debate remains open with the aim of answering the following question: Does the implementation of SODIS-based interventions to improve access to safe drinking water result in a reduction in the prevalence of diarrhea in communities? Several essays were carried out in different contexts to bring an answer to this question. Most trials described in the literature measured the impact of SODIS use on the prevalence of diarrheal diseases in children under 5 years. Findings from nearly all of these studies yield a positive answer to this question, namely, does SODIS reduce the incidence, severity, and risk of diarrhea in children? [26,27,28,29,30,31,32,33,34]. Readers interested in some details about the findings of the various trials are directed to the supplementary material.

Overall, test results show that providing PET bottles and training on how to perform SODIS in communities results in a lower prevalence of disease in children (1.9%) compared to matched controls (13.9) during a cholera outbreak [27]. SODIS use also resulted in a lower prevalence of severe cholera episodes among SODIS users (48.8%) than non-users (58.1%) in a Maasai community, Kenya [28].

Regarding other types of diarrhea (including cholera) studies show that the use of SODIS resulted in lower prevalence values (7.58 - 22.8%) compared to the corresponding controls (31.43 - 31.8%) [30,31]. Graff et al. [31] reported lower values of diarrhea prevalence (18%) when considering data from families that fully complied with the intervention. A reduction in the occurrence of diarrheal episodes was also reported among SODIS users (1.7 child / year) compared to non-users (2.7 child / year) in an urban slum in Vellore, India [29]. Likewise, the use of SODIS has been reported to result in reduced incidence of dysentery as well as non-dysentery diarrhea with an incidence rate ratio (IRR) of 0.50 to 0.55 and 0.37 to 0.73 , respectively [32,33]. Bitew et al. [34] also reported a significant reduction in the incidence of diarrhea with an adjusted IRR of 0.60. Overall, the adoption and use of SODIS by communities results in a 40 to 75.88% reduction in the risk of diarrhea in children under 5 years [29,30,31,32,34].

The trial conducted by du Preez et al. [33], in addition to reporting a significant reduction in episodes of dysentery and non-dysentery diarrhea, also reported that anthropometric measurements (height and weight) were significantly higher in children under 5 years of age using SODIS. It was found that children using SODIS were on average 0.8 cm taller and 0.23 kg heavier. The assertiveness of these findings, especially the contribution of SODIS in increasing anthropometric measurements, was criticized by Hunter et al. [35]; these authors stated that the anthropometry of the children in this study is not an objective measure of outcome. In addition, they highlighted that the technical error of the interobserver measurement is 1.4 cm, therefore greater than the difference reported between the two populations. Arnold et al. [36] in turn, while applauding the relevance of these findings, drew attention to the need to apply a blinded methodology to reduce the chance of bias interference in inferences in trials that aim to measure the impact of SODIS use on the prevalence of diarrhea.

The only trial in the literature that reported a statistically non-significant difference in the incidence of diarrhea between children under 5 years of age using SODIS and corresponding controls was carried out in Bolivia [37]. The study reported that the incidence rate of diarrhea in children using SODIS was 3.6 compared to 4.3 episodes / year in the corresponding control group. The authors attributed these findings to the lower rate of adherence of the population (32.1%) to SODIS. For McGuigan et al. [7] the study findings may have resulted from a failure of SODIS to reduce risk, or a failure of the intervention to produce results in line with the known efficiency of SODIS to result in a significant reduction in the risk of diarrhea. In a study carried out by Christen et al. [38] it was found that the population's adherence to SODIS was strongly determined by socioeconomic factors. On the other hand, high risk perception and health concern, as well as the participation of women and the presence of a malnourished child living in a house, are predictors of a high chance of adherence to SODIS.

Taking into account all the findings of the trials that aimed to measure the implication of the use of SODIS in the prevalence of waterborne gastrointestinal diseases, specifically diarrhea, it can be said that the adoption of SODIS significantly reduces not only the number of cases of diarrhea in children, but also the number of episodes per person and the severity of symptoms. The authors agree that improving the quality of drinking water by introducing SODIS into the community can have as high an impact on reducing diarrhea as the impact achieved by multiple WASH interventions (consisting of combined water, sanitation and hygiene measures) [39,40,41,42].

However, the ability of SODIS-based interventions to reduce diarrhea in children in communities has not yet reached consensus in the literature. Authors who conducted systematic review studies followed by meta-analysis, aiming to elucidate the impact of SODIS-based interventions on diarrhea prevalence, reached different conclusions. The study carried out by Darvesh et al. [43] concluded that water quality improvement interventions based on point-of-use (POU) water disinfection methods, including SODIS, chlorination, and flocculant-disinfectant, resulted in a 31% decrease in the risk of diarrhea in children. Clasen et al. [20] in turn concluded that SODIS-based interventions are likely to reduce the prevalence of diarrhea by about a third. Greater effects are observed when there is greater adherence and/or when the intervention includes the provision of reactors for disinfection and bottles for the safe storage of treated water. In contrast, Hunter [44] found that the beneficial effects of microbiological methods of water treatment in the POU (SODIS, chlorination and coagulation-chlorination) reported in the literature are strongly influenced by the bias introduced by the lack of blinding and high heterogeneity of the data. When bias resulting from the lack of blinding methodology was considered in the analyses, there was no evidence that SODIS was beneficial [44,45]. The most recent review study on this topic was performed by Soboksa et al. [46]; these authors concluded that the use of SODIS resulted in a reduced risk of diarrhea in children and adolescents (1 to 15 years) by 38%. However, the authors state that the risk of bias and the heterogeneity of the included studies prevented drawing definitive conclusions, which is why they state that more high-quality trials (based on innovative methodologies and with no ethical conflicts) are still needed to elucidate whether SODIS-based interventions reduce diarrhea [47].

Immune gains from SODIS

The use of SODIS as a method of providing drinking water has been widely associated with a reduction in the frequency and severity of diarrhea, particularly among children [20,30,32,33]; these results have been attributed to the consumption of water free of viable pathogens. The immunogenicity of sun-inactivated pathogens in water, as well as the immunological implications in people who consume SODIS-treated water, have drawn the attention of few researchers.

Ssemakalu et al. [21] hypothesized that drinking SODIS-treated water containing at least a density of inactivated *Vibrio cholerae* corresponding to the infectious dose (8-11 log in people with normal gastric acidity, or 4-6 log in people with hypochlorhydria [48]) would result in the induction of immunological changes with protective effects against cholera. One year later, these authors examined the effect of SODIS-inactivated *V. cholerae* on cytokine secretion (IL-1α, IL-1β, IL-6, IL-7, IL-10, IL-12p40, IL-12p70, IL-12 - 12-15, IL-23 and IL-27) and chemokines (MIP-1α, MIP-1β, MIP-2, RANTES and TNF-α) by JAWS II dendritic cells *in vitro* [49]. For this, cultures of *V. cholerae* inactivated by SODIS (7h of sun exposure) were incubated with JAWS II cells for 48h. It was found that SODIS-inactivated *V. cholerae* induced the secretion of a diverse range of cytokines and chemokines by JAWS II cells. The diversity of secreted pro-inflammatory cytokines and chemokines was greater in the treatment with SODIS-inactivated *V. cholerae* than that observed in treatments with heat and chemically inactivated cultures, as well as with lives *V. cholera*. Furthermore, the concentration of cytokines and chemokines in treatments involving SODIS-inactivated *V. cholerae* cultures was significantly higher than that measured in unstimulated JAWS II cells. However, the concentration of cytokines and chemokines was lower in treatments with SODIS-inactivated *V. cholerae* compared to treatment with viable *V. cholerae* cultures (Figure 2). The authors hypothesized that the cytokine and chemokine profile of JAWS II cells incubated with SODIS-inactivated *V. cholerae* cultures would likely induce a Th2 immune response. A similar result was obtained in a study in which differentiated macrophage-like THP-1 cells were stimulated with either live or heat-inactivated *V. cholerae* cultures [50]. Weil et al. [50] observed that IL-23 secretion was higher (5.6-fold higher) in cells exposed to viable cultures of *V. cholerae* than in cells exposed to heat-inactivated ones.

The results of these two studies corroborate other studies that reported that infection by *V. cholerae* results in the induction of longer lasting (≥ 3 years) immune protection [51] than that induced by inactivated *V. cholerae* (~ 2 years) [52]. The induction of longer-lasting immune protection was associated with IL-23 secretion. IL-23 secretion during the induction of immune changes is desirable as it is associated with promoting Th17 differentiation into follicular helper T cells, which are responsible for maintaining and supporting the generation of long-term memory B cells in humans. On the other hand, unlike the findings by Weil et al. [50], Ssemakalu et al. [49] reported greater IL-23 secretion by JAWS II cells incubated with SODIS-inactivated *V. cholerae* than those incubated with live (suspended in water) or heat-inactivated (65°C + formalin 1,5 %) *V. cholerae*. The difference in the findings reported in these two studies can be attributed both to the differences between the *V. cholerae* strains used, between the culture inactivation methods and the difference in the tested immune cell models.

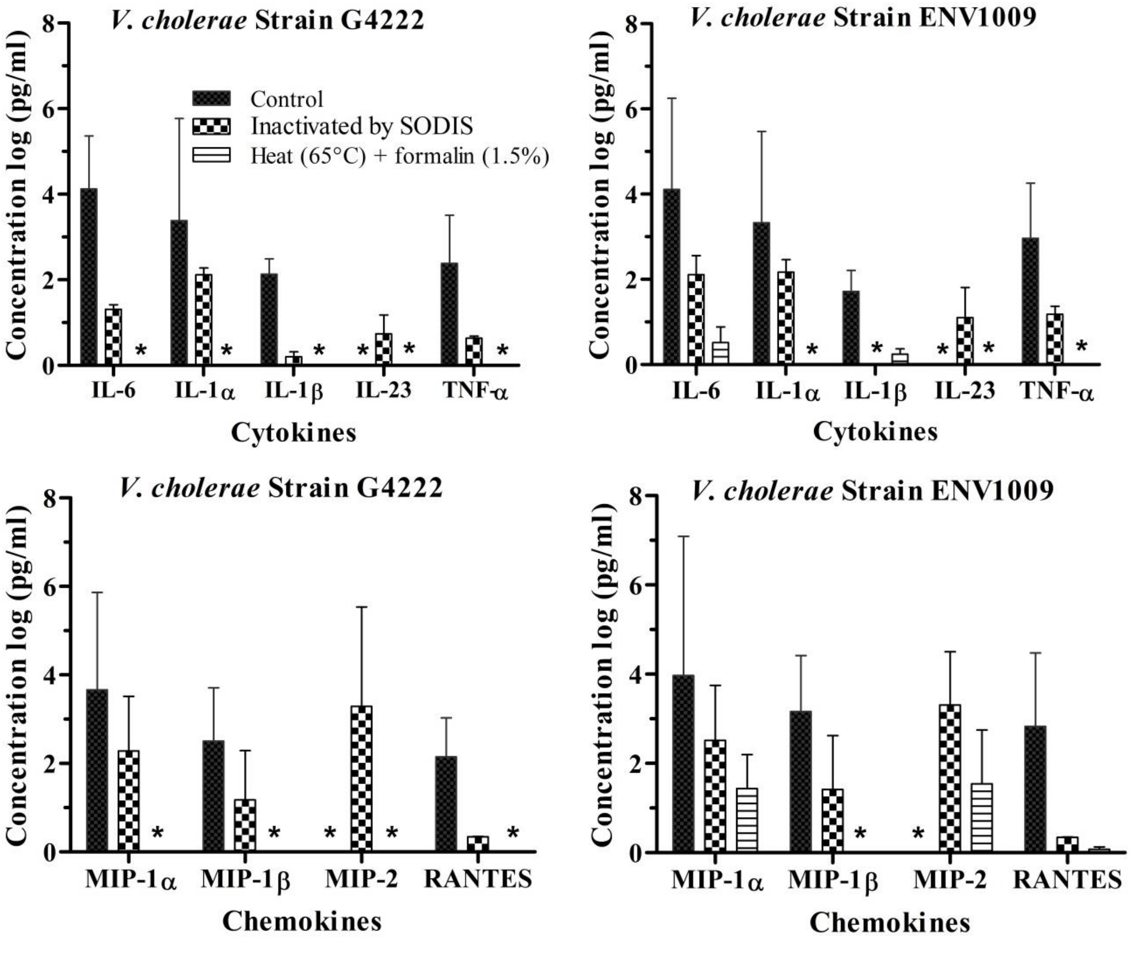

FIGURE 2 *In vitro* secretion profile of cytokines and chemokines by JAWS II dendritic cells induced by SODIS-inactivated *Vibrio cholerae*. Control – Live *Vibrio cholera* kept in the dark. (*) - below detection limit (< 3.2 pg/ml). IL – interleukin, TNF - tumor necrosis factor, MIP - macrophage inflammatory protein, RANTES - regulated on activation, normal T cell expressed and

secreted. Figure based on selected data from Ssemakalu et al. [49], with permission: http://creativecommons.org/licenses/by/4.0/

The findings by Ssemakalu et al. [49] suggest that the use of SODIS results in inactivated cultures of *V. cholerae* with more desirable immunogenic properties and, in addition to SODIS providing safe drinking water, consumption of this water has the potential to induce a long-term protective immune response against cholera.

Ssemakalu et al. [53] demonstrated that SODIS-inactivated cultures of *V. cholerae* induce *in vitro* maturation of JAWS II dendritic cells. In this study, the cultures of *V. cholerae* were inactivated by SODIS through suspension in water contained in a polystyrene bottle followed by exposure to direct solar radiation for 7 hours. The percentage of JAWS II cells expressing surface maturation markers (CD40, CD54, CD80, CD83, CD86, MHC-I and MHC-II) was measured and the results of tests with the hypervirulent strain (G4222) and with the environment (ENV1009) of *V. cholerae* are summarized in Figure 3. The authors concluded that the phenotype of dendritic cells generated after co-incubation with SODIS-inactivated *V. cholerae* is capable of inducing a type 1 T cell immune response.

Ssemakalu et al. [54] demonstrated that SODIS-inactivated *Salmonella* Typhimurium is capable of inducing bactericidal antibodies against *S.* Typhimurium in a murine model. In this study, the bacteria were suspended in water contained in a polystyrene bottle, which was then exposed to the sun for 8 h. SODIS-inactivated bacteria were centrifuged and resuspended in PBS at a density of 1 x 10^9 CFU/100 µl. 100 µl of the *S.* Typhimurium suspension was administered by oral gavage to BALB/c mice, with a booster administration performed on day 14 and 28 after the first administration. A significantly increased secretion of interferon-gamma (IFN-γ) was observed in mice that received SODIS-inactivated *S.* Typhimurium. Furthermore, it was observed that the serum antibodies secreted in mice that received SODIS-inactivated bacteria were functional, that is, they triggered a significant inhibition of the growth of *S.* Typhimurium compared to the control (mice that did not receive SODIS-inactivated bacteria).

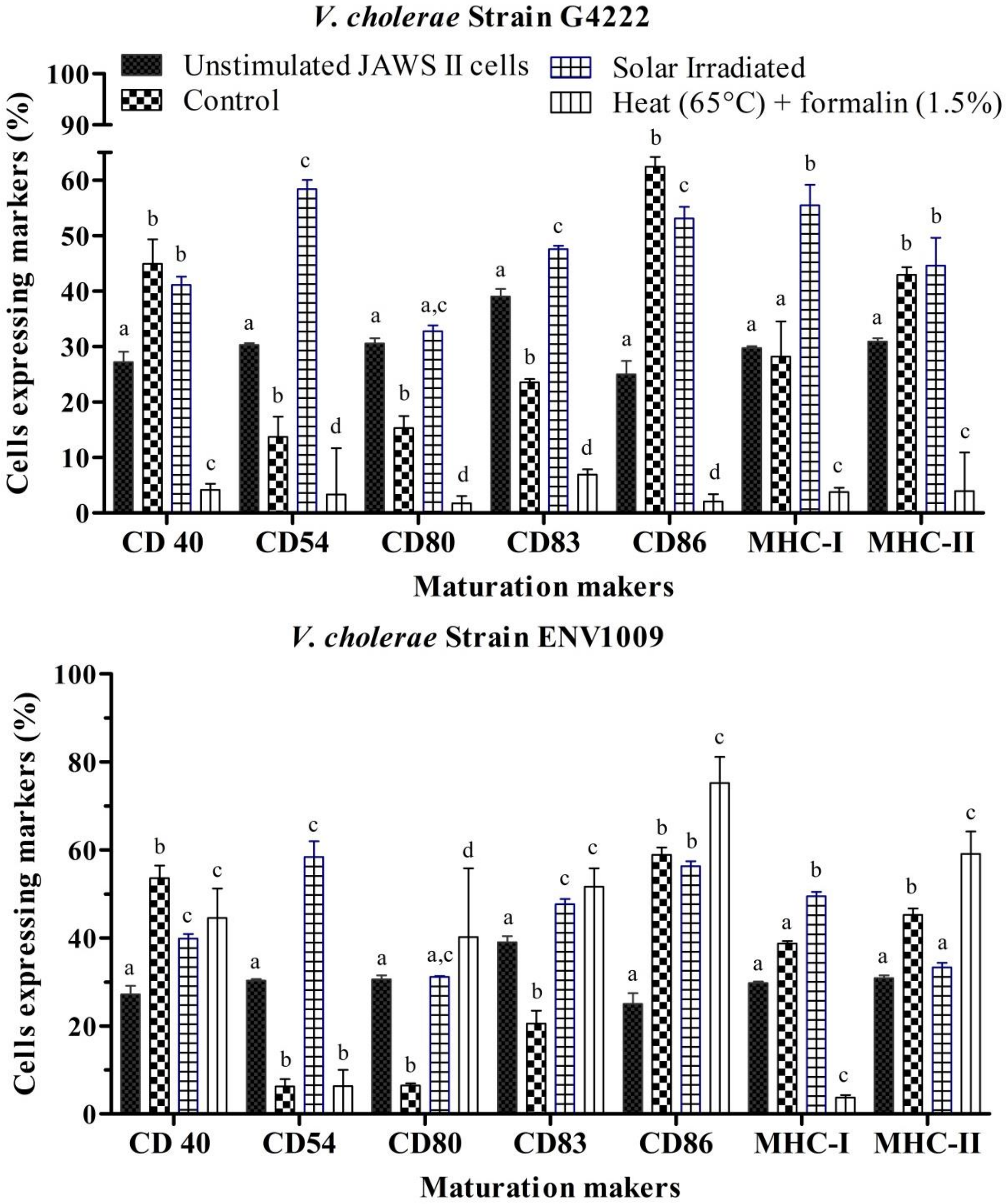

FIGURE 3 *In vitro* expression profile of maturation markers of JAWS II dendritic cells induced by SODIS-inactivated *Vibrio cholerae*. Control – Live *Vibrio cholera* kept in the dark. Columns marked with different letters per subgroup mean a statistically significant difference ($p < 0.05$). CD - cluster of differentiation, MHC - major histocompatibility complex. Figure based on selected data from Ssemakalu et al. [53], with permission: http://creativecommons.org/licenses/by/4.0/

Final remarks

Conventional SODIS is an inexpensive method of treating potable water at home, the effectiveness of which has been robustly documented. However, the effectiveness of SODIS-based interventions in reducing the prevalence of childhood diarrhea is not consensual, among the results of field trials and part of systematic review studies with meta-analysis. Some studies that performed a pooled analysis of data collected from field trials reported conclusions inconsistent with those obtained by all (except [37]) field trials [26,27,28,29,30,31,32,33,34]. The authors point out that the remarkable heterogeneity between field trials, as well as the non-use of the blinding method (to minimize the risk of bias) prevents the establishment of definitive conclusions [44,45,46].

In any case, it is important to remember that this divergence between studies refers to the impact of interventions based on SODIS in reducing the prevalence of diarrhea and not in the effectiveness of SODIS in inactivating the etiological agents of diarrhea. So, although the discussion is based on the methodological quality of the field trials, the core of the discussion needs to focus on how SODIS is delivered to people and how they receive it and make use of it over time.

One of the most important limitations of conventional SODIS lies in the fact that its impact on the prevalence of diarrhea depends on the behavior of each person or family to perform water disinfection correctly every day. Discussions about the limitations of conventional SODIS and ways to overcome them have recently taken place [9,24,55]. However, just as high-quality studies are needed to assess the impact of SODIS-based interventions on diarrhea prevalence, so are efforts to identify the best ways to deliver SODIS technology to communities. These efforts should also consider the evaluation of different technological proposals to overcome the limitations of conventional SODIS. Proposals that increase the productivity of SODIS, and those that reduce the workload resulting from the daily routine of filling bottles and placing them in the sun need to be prioritized.

Although more studies are still needed, the evidence currently available in the literature suggests that the epidemiological gains achieved from the use of SODIS result from the combination of the effect of the consumption of biologically safe drinking water and the ingestion of non-viable microorganisms with important immunogenic properties. Reports of reduced episodes of diarrhea and, as well as episodes of severe diarrhea, among SODIS users [26,27], even in a situation where 86% of children also drank untreated water [29], or during the cholera outbreak [31], corroborate studies that suggest a protective immunological effect in SODIS users [21,54].

The ability of SODIS-inactivated pathogens to induce immunological changes that result in protective effects is related to the mechanism of microbial inactivation by the sun. Microbial inactivation during SODIS is mainly due to the biocidal effect of solar UV radiation (A and B) or the synergy of UV and solar heat [56]. The contribution of photosynthetically active radiation is relatively small [57]. These mechanisms are responsible for compromising metabolic activity and reducing the ability of microorganisms present in water to induce cytotoxicity [58]. It has been reported that during SODIS, a wide variety of cellular structural and enzymatic proteins are affected by carbonylation and aggregation, in a pattern of damage similar to the oxidative process [59]. This damage occurs, however, without compromising much of the immunogenic properties of the microorganisms [49,53,54].

It is important to note that although the reduced risk of diarrhea persists under all circumstances among SODIS users, the induction of immunological changes that result in protective benefits occurs when raw water is contaminated with at least a density equal to or greater than the infectious dose of the pathogen [21,54]. In this case, there is a greater chance that the use of SODIS will result in immune gains during outbreaks [21]. These protective effects may be long-term, as it has been shown that pathogens inactivated by SODIS can induce immunological changes that lead to the generation of long-term memory B cells in humans [49,50].

CONCLUSION

Interventions to improve access to safe drinking water based on SODIS have the potential to reduce the prevalence and severity of diarrhea in children, especially when there is high adherence. However, this conclusion is provisional and awaits confirmation from studies with a low risk of bias.

The impact of SODIS on diarrhea prevalence is determined by how SODIS is delivered to communities and how they receive and make use of it over time.

There is a chance of inducing immunological changes that result in short-term and long-term protective effects against waterborne pathogens in SODIS users. This induction, which can result in protective immunological effects, is expected mainly during outbreaks and more frequently in endemic areas.

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Conflicts of interest

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Availability of data and material

Not applicable

Ethics approval

Not applicable

Consent to participate

Not applicable

Consent for publication

Not applicable

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CAPÍTULO VI

Artigo intitulado “Why do Low-Cost Point-Of-Use Water Treatment Technologies Succeed or Fail in Combating Waterborne Diseases in The Field? A Systematic Review” Publicado na revista Journal of Environmental Chemical Engineering http://dx.doi.org/10.1016/j.jece.2023.110575. Parte dos resultados é apresentados no Material Suplementar – APÊNDICE XIII.

Why do Low-Cost Point-Of-Use Water Treatment Technologies Succeed or Fail in Combating Waterborne Diseases in The Field? A Systematic Review

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ABSTRACT

In a world where the consequences of inequalities in access to safe drinking water persist, Household Drinking Water Treatment Technologies (HDWT) remains the most readily available and promising alternative solution to prevent waterborne diseases. While successful cases of combating waterborne diseases with HDWT have been documented, there are also reports of failures in reducing water-related illnesses. Understanding the reasons behind these inconsistent results is crucial. This work aimed to identify and critically discuss barriers, enablers, and technology delivery strategies for HDWT-based interventions to improve drinking water safety. Data from 147 articles covering Solar Disinfection, Chlorination, Flocculation-Disinfection, BioSand Filter, and Ceramic Water Filter were extracted from a total of 11,982 systematically retrieved records. Among the identified factors, 77 barriers and 76 enablers were distributed across different domains: psychosocial (37.7, 47.4%), promotion (22.1, 26.3%), technology (28.6, 10.5%), economic (9.1, 14.5%), and environmental (2.6, 1.3%) for barriers and enablers, respectively. Technology delivery strategies primarily included water education and technology promotion, training for technology usage, provision of HDWT through donation or promotional sale, donation of safe water storage, technical assistance, and the use of a diarrhea control diary. All barriers and enablers affect the initial adoption, regular, and sustained use of HDWT and should be considered when planning and implementing interventions. The health impacts of interventions decreased over time since HDWT adoption. Adequate user training, HDWT donation, and high compliance are important predictors of success for HDWT-based interventions. In general, identifying and exploring the listed enablers can help overcome many of the reported limitations.

Keywords: SODIS, Chlorine, Flocculant-disinfectant, BioSand Filter, Ceramic water filters, Barriers, Enablers, Technology delivery strategies.

1. Introduction

Low-cost Household Drinking Water Treatment Technologies (HDWT) are recognized as one of the most suitable short- and medium-term tools to prevent high human mortality (829,000 annual deaths) Low-cost Household Drinking Water Treatment Technologies (HDWT) are recognized as one of the most suitable short- and medium-term tools to prevent high human mortality (829,000 annual deaths) caused by waterborne diseases resulting from the consumption of unsafe water [1,2]. These technologies are particularly valuable in developing country settlements that lack access to treated drinking water distribution networks, where establishing centralized systems for safe drinking water provision poses significant challenges or remains a distant aspiration [3]. These countries bear the burden of the highest population segments without access to clean drinking water, and they suffer from elevated mortality rates due to diarrheal diseases. Rivers, lakes, and shallow wells, which serve as their primary water sources, are often heavily contaminated [4,5,6]. It is important to note that users frequently consider water from these sources safe for consumption without treatment based on visual inspection alone [7].

Solar disinfection (SODIS), chlorine, flocculant-disinfectant, BioSand Filter (BSF), and Ceramic Water Filter (CWF) are among the notable HDWT recognized for their effectiveness, affordability, popularity, and successful application in interventions aimed at improving the safety of drinking water [8,9]. The impact of HDWT-based interventions to improve the quality and safety of drinking water in reducing the risk of diarrhea and cholera (≥ 50%) is consistently documented [10,11].

SODIS is a method that uses the biocidal properties of ultraviolet (UV) radiation and heat from the sun to inactivate microorganisms in water. Its effectiveness has been widely demonstrated against almost all representatives of microbial groups [12,13,14]. Conventional SODIS consists of placing untreated water in containers (~ 1.5 – 25 L) that transmit UV radiation and exposing them to the sun for at least 6 hours on sunny days [15,16,17,18]. Improvements to maximize its effectiveness [19,20,21] and productivity to enable its application in large-scale drinking water supply are described in the literature [22,23]. Immunological and epidemiological gains from using SODIS are also well documented [24,25]. Typically, there is a 20-75% reduction in the risk of diarrhea [26,27].

Chlorination is a low-cost, well-established and historically used method for the chemical treatment of drinking water. This approach includes the addition of chlorine-based compounds (e.g. sodium hypochlorite, chlorine tablets) to water to establish a residual free chlorine concentration of 0.2–0.5 mg/L or more (depending on the situation), but not more than 5.0 mg/L [28,29,30]. At these concentrations chlorine is as capable of eliminating most known pathogenic microorganisms (with exceptions, e.g. *Cryptosporidium* oocysts, Giardia and *Acanthamoeba* cysts [31,32]) within 30 - 60 minutes of contact time, as well as preventing their regrowth in water [33]. While there is health concern with the use of chlorine, given the possibility of formation of a wide variety of disinfection by-products (DBPs) in water [34], the concentration of these DBPs under field conditions has not exceeded WHO’s guidelines [35]. Promoting household chlorination, independently or in combination with other sanitation measures, has resulted in consistent reduction (35-71% or 41% respectively) in the risk of diarrhea [36,37].

The flocculant-disinfectant treatment technology takes advantage of the synergistic sanitizing effect of a flocculant and chlorine. It was developed to overcome the problem of limited microbicidal effectiveness of chlorination when used to treat water with high turbidity [38]. Under these conditions, it is recommended to add proportionately higher doses of chlorine, increasing the taste and smell, as well as the of DBPs formation in the treated water, especially if the organic matter content is high [30,39]. The flocculant-disinfectant is normally a powder or tablet which, when added to water, triggers precipitation, coagulation and flocculation of particulate matter (metals, organic matter, microorganisms), releasing, at the same time residual free chlorine. The treated water is visually cleaner, and chemically, physically and microbiologically safe for drinking [40]. The reduction in the prevalence and risk of diarrhea (25 – 64%) with household use of a flocculant-disinfectant is consistently documented in the literature [10,29,41].

The BSF is a water purification technology that combines biological and physico-chemical processes that occur in the sand filter media, to remove contaminants from the water [42]. The BSF is essentially constituted by a column composed of successive layers of sand and gravel of different granulometries, containing microbial biofilm established on the surface of its upper layer [42,43]. In addition to being effective in removing pathogenic microorganisms, turbidity and some chemical contaminants from water [44,45], promoting the household use of BSF has been implicated in significantly reducing the risk of diarrhea [46,47,48].

The CWF is a low-cost technology for drinking water treatment that, similarly to BSF, makes use of physical and chemical processes to remove different contaminants from the water, especially microorganisms. Commonly it is made of a terracotta structure containing a microporous filtering region, they may or may not be impregnated with colloidal silver [49,50,51]. When the filtering region is not part of the filter wall, a filtering component, also called “a candle”, is incorporated into the CWF [52]. CWF have been widely demonstrated as effective [53,54,55], sustainable [50,56] and socially acceptable [51,57], capable of significantly reducing the risk of diarrhea when promoted as a household drinking water treatment technology [58,59,60,61].

Despite substantial epidemiologic and laboratory evidence of the positive health impacts of HDWT, questions remain on the ability of this approach to consistently and sustainably provide positive health impact [25,62,63,64,65].

Concerns about the uncertainty or the extent to which the widespread use of HDWT technologies results in protective gains against waterborne diseases are based results from field studies that did not observe a protective effect (especially when adherence was low) [62,63,66]. Additionally, results of systematic reviews suggest a lack of protective effect, especially when the lack of blinding methodology in primary studies is considered [67,68,69,70]. On the other hand, there are many field studies and systematic reviews with meta-analyses reporting a protective effect by promoting the use of HDWT [11,27,48,71,72]. It is important to note that success in fighting waterborne diseases with household drinking water treatment technology reflects previous success in promoting and maintaining behavioral changes at the individual, domestic, community and structural levels, as well as in the selection of the appropriate technology [73,74,75,76]. On the other hand, the failure of some plausible interventions when implemented at scale may also reflect a failure of delivery strategies rather than an ineffective intervention [77]. How well intervention programs are implemented determines the acceptability, adoption, compliance, and sustained use of these technologies [78]; and high adoption and usage compliance (> 90%) lead to substantial gains in diarrhea protection, even when the technology's effectiveness in removing pathogens is relatively lower [79,80,81]. The correct definition of “how an intervention program is implemented” is context-specific and conditioned by different factors among which barriers, enablers and technology delivery strategies are listed. Although these factors vary with HDWT and context, it is desirable to systematize them to allow an increasingly comprehensive and holistic understanding; yet this information is sparsely or partially available [30,78,82,83]. The present study aims to systematically review the factors that constitute barriers and facilitators for the success of HDWT-based interventions to combat waterborne diseases. The work also aims to bring together the delivery strategies used by different interventions that aimed to promote these technologies.

2. Methods

2.1. Article recovery strategy

The search aimed to retrieve scientific articles that deal with factors that constitute barriers and enablers for success in combating waterborne diseases through interventions using low-cost HDWT. Additionally, it sought articles reporting the technology delivery strategies employed during these interventions, along with their impacts on adoption, adherence, sustainable use, drinking water quality, and reduction of diarrhea. The study was conducted following the PRISMA 2020 guidelines [84] (Fig. 1).

Searches were performed between September 4 and 23, 2022, in the following databases, PubMed, Web of Science, Scopus, MDPI, EMBASE, Cochrane library and ProQuest, using a combination of the following terms: “Biosand filter”, “slow sand filters”, “Solar disinfection”, “Household water chlorination”, “Point-of-use water treatment”, “Ceramic water filter”, “Flocculant”, “Diarrhea prevalence”, “Waterborne prevalence”, “Barriers”, “Enabler”, “Acceptance”, “Adoption”, and “Compliance”.

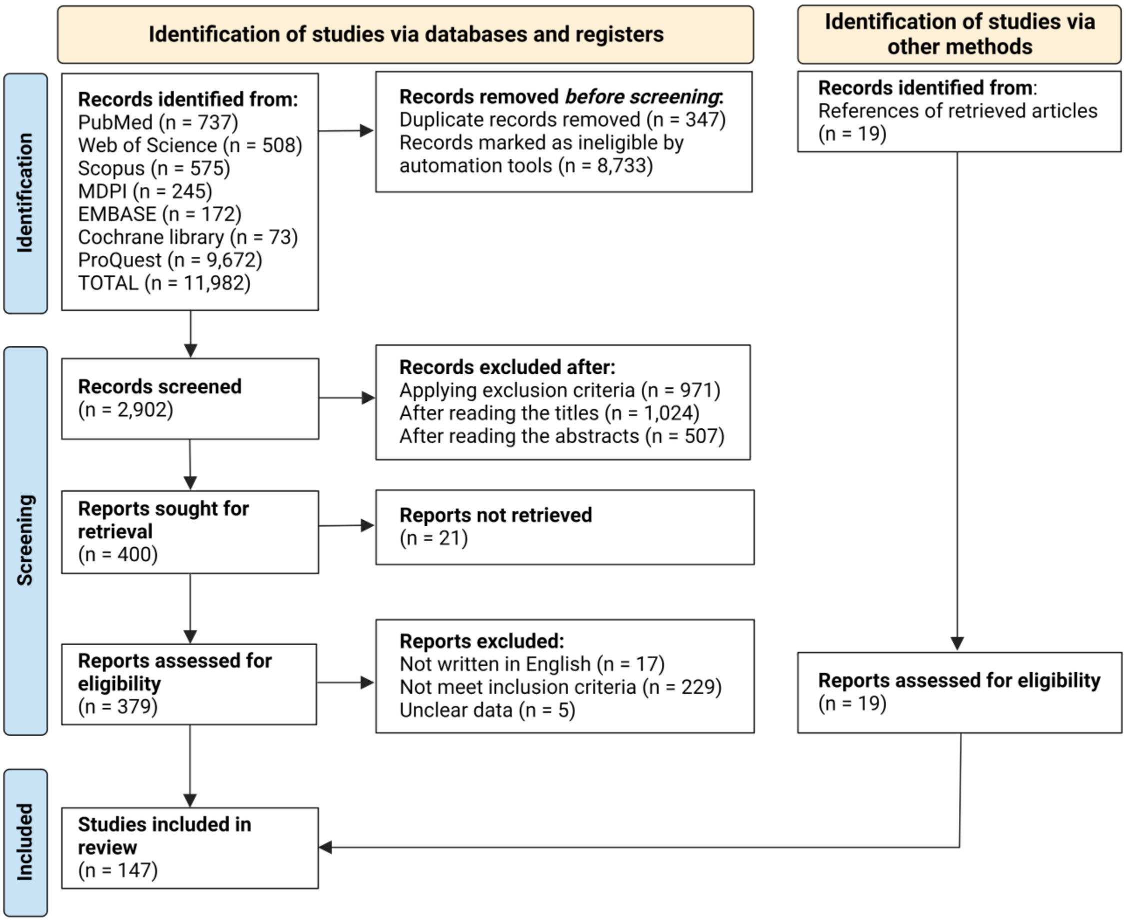


Fig. 1. Strategies for retrieving and selecting articles presented through the PRISMA flowchart.

2.2. Selection and exclusion criteria

Were selected original and review scientific articles written in English, published by both indexed and non-indexed journals that undergo peer review. There were no restrictions on the publication period. Articles reporting data of interest (barriers, enablers, delivery strategies, adherence rates, compliance, sustainability, water quality, diarrhea measurement) obtained from real-life situations promoting the use of HDWT were included. Studies reporting data obtained from experimental conditions under laboratory and/or simulated conditions (with few exceptions) were excluded. The mentioned few exceptions pertain to studies that assess the durability of specific technologies within controlled real-life or simulated environments, which were not excluded from consideration.

2.3. Data extraction

Reading the full text of the included articles was performed to extract the information of interest, which included qualitative and quantitative data. The qualitative data included country (where the study was carried out), barriers, enablers, and HDWT delivery strategy.

Barriers or enablers – refer to all factors that have been identified as limiting or boosting to the objectives of HDWT-based interventions, respectively [85]. For each HDWT, the barriers and enablers were grouped into different domains, namely: Psychosocial, Promotion, Technology, Economic and Environment, inspired by the previously described HDWT sustainability assessment criteria [86], as well as by the Integrated Behavioral Model of Water, Sanitation and Hygiene (IBM-WASH) [73].

Psychosocial – groups factors related to Risk, Attitudes, Norms, Abilities, and Self-Regulation (RANAS) [243], as well as those related to acceptance and availability of technology [86] that fall into the following IBM-WASH categories "Psychosocial and Contextual Factors" [73]. Promotion – This domain groups together all factors related to technology introduction and delivery strategies, as well as actions to establish desired behaviors, including partnerships, stakeholder motivation, and frequency and duration of activities. Technology – this domain groups the factors based on the technical attributes of the HDWT, including its performance, operability, and implementability [86]. Economic – groups all factors based on financial determinants, including perceived cost, acquisition and maintenance costs, payment methods, willingness to pay, and economic status [86]. Environment – integrates the environmental factors that determine HDWT usage and performance.

Delivery strategy – refers to the mechanisms through which the intervention was introduced and conducted in the target communities. Quantitative data included duration of intervention, sample size, as well as rates of initial adoption, adherence, and diarrhea reduction. The delivery strategies reported in the different studies, and which allow a consistent comparison of the corresponding data, are: (1) Water education and technology promotion (provision of information on the need for consumption of treated water and on the importance of specific HDWT). (2) Training to use technology (training on water treatment practice using a specific HDWT); (3) Technology donation (free distribution / free distribution and installation of HDWT). (4) Technology promotional sale (low cost sale of a HDWT and/or safe water storage containers); (5) Safe storage donation (free distribution of container for the treatment and/or safe storage of water). (6) Technical assistance (routine home visits to reinforce the need for water care, as well as to encourage and assist in the correct and sustained use of HDWT), and (7) Diarrhea control diary (training on recording diarrhea at home through a diary, before and/or after starting HDWT use).

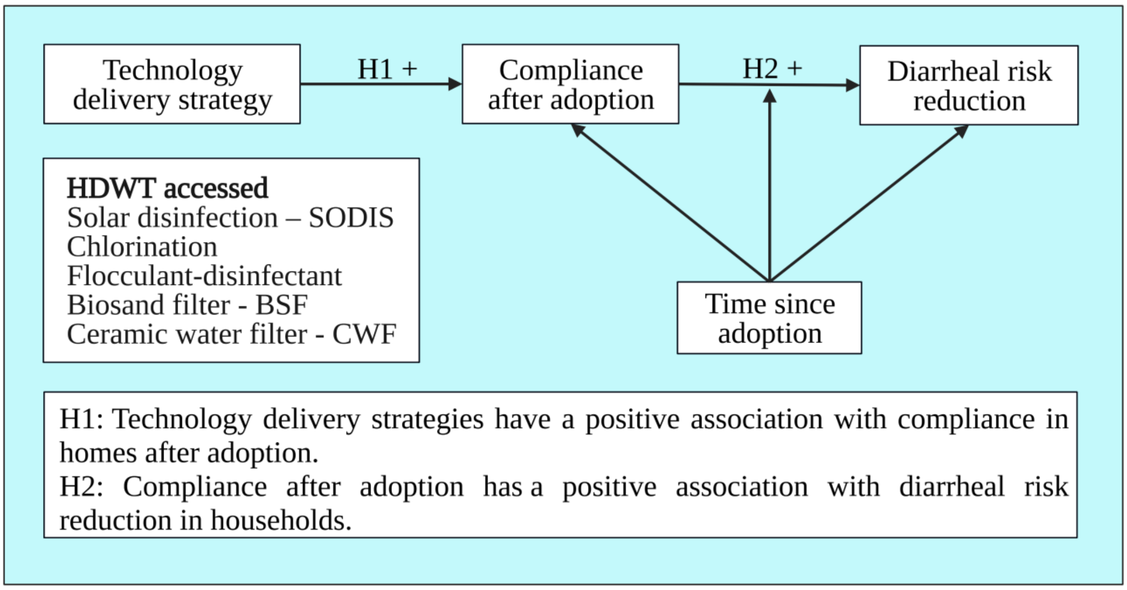
2.4. Data analysis procedure

Data analysis included frequency comparison and regression analysis. Frequency comparison focused on qualitative variables, specifically barriers and enablers. Frequencies were calculated overall or specifically for each of the HDWT, based on the number of studies reporting each of the barriers and enablers.

Regression analysis was applied to determine how different technology delivery strategies interact with quantitative variables. For this we work mainly with five variables, namely, (i) the number of households participating in the intervention; (ii) technology delivery strategies; (iii) adoption (%); (iv) compliance after adoption (%); and (v) diarrheal disease reduction (%), based on the model and hypotheses presented in Fig. 2. Each of the technology delivery strategies were classified for absence or presence in different corresponding studies for each HDWT using binary value (i.e. 0 or 1, respectively). Values reported in percentages (e.g., adoption (%), compliance (%), and diarrheal risk reduction (%)) were converted to a natural logarithm scale to avoid potential bias [88]. The values of the adoption, adherence, and risk reduction of diarrhea variables were used to calculate the real corresponding number of households, which adopted, achieved compliance, and achieved a significant reduction in the risk of diarrhea. Finally, the variable “Time” was used as a control variable in our model, and this variable also evaluated the effect of interaction with adherence.

Afterward, we performed a set of hierarchical ordinary least squares (OLS) regression models in RStudio. Because several regression models were performed, we only reported the ones with significative results, as well as, their F-test, R^2, Adjusted R^2, and R^2 Change. First, we included Time and each Technology Delivery Strategy individually to check their association with

Compliance in each water quality method to test our H1. Second, to test H2, was added Time, Compliance, Time x Compliance, and each Technology Delivery Strategy individually on Diarrheal Disease Reduction.



H1: Technology delivery strategies have a positive association with compliance in homes after adoption.
H2: Compliance after adoption has a positive association with diarrheal risk reduction in households.

Fig. 2. Regression model and hypotheses used to infer the role of technology delivery strategies on performance indicators of HDWT-based interventions.

In addition, tests like normality, linearity, homoscedasticity, and multicollinearity were completed during the regression analysis. For collinearity, we plotted the partial regressions for the independent variables. In the case of homoscedasticity, we examined it in plots of standardized residuals against a predicted value. All these requirements were met to proceed with the regression analysis. Also was evaluated the multicollinearity issue for our independent variables, as suggested by Hair *et al.* [89]. The presence of multicollinearity indicates that the regression estimates are unstable and have high standard errors. Our results indicate a variance inflation factor (VIF) below the maximum allowed threshold of 10 [89], suggesting multicollinearity is not an issue in our study. Finally, to check normality, were assessed only our non-binary variables (i.e., Time, Compliance, and Diarrheal risk reduction) for each HDWT, and was confirmed that our variables are normally distributed since their skewness and kurtosis values fell between the threshold of ± 2.58 as previously recommended [89].

3. Results and discussion

Using the search strategy and the aforementioned databases returned 11,982 documents, of which 147 articles were selected after applying the exclusion and inclusion criteria (Fig. 1). The selected articles were published between 1985 and 2022 and report results of studies carried out in 37 countries across Africa, America, Asia and Oceania, as detailed in Fig. 3.

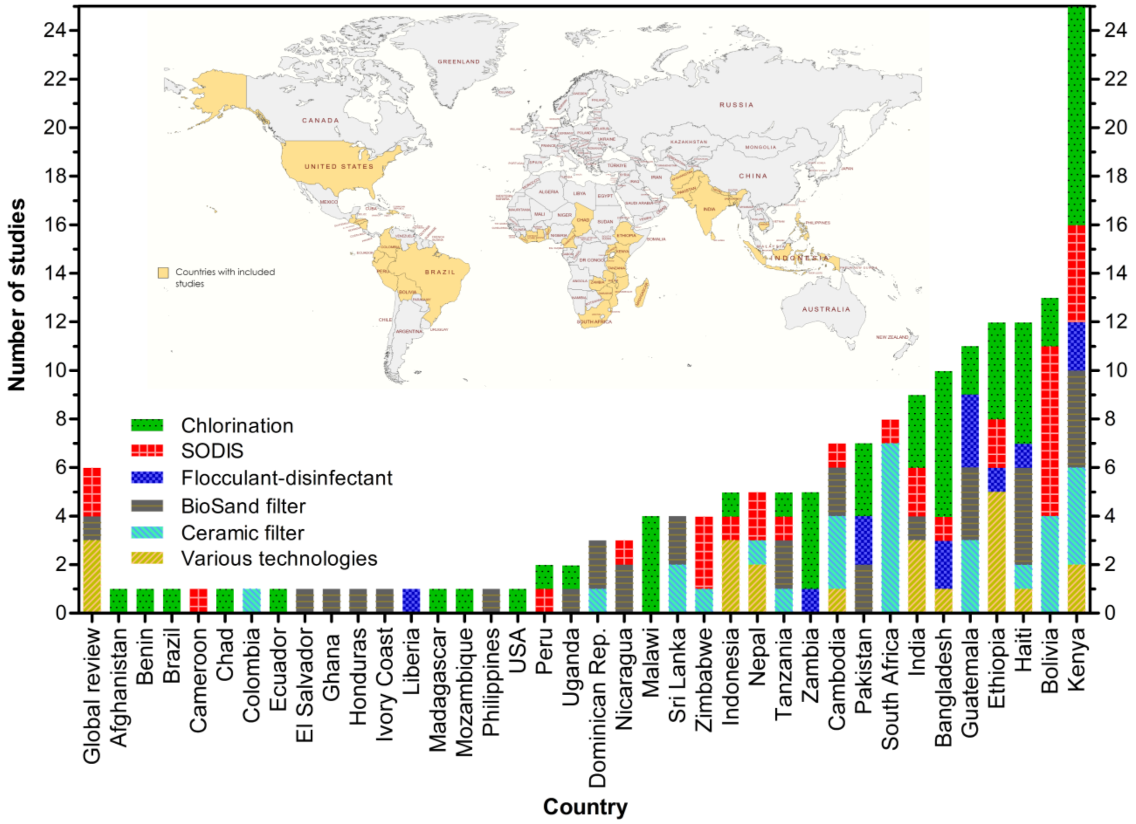


Fig. 3. Spatial distribution of selected studies.

3.1. Barriers and enablers of HDWT-based interventions

The factors identified as barriers or enablers for success in combating waterborne diseases through interventions based on HDWT are presented below. The barriers and enablers mentioned are grouped into different domains, namely: psychosocial, promotional, technology, economic and environmental, inspired by the previously described HDWT sustainability assessment criteria [86].

Overall, a total of 77 barriers and 76 enablers were identified. The barriers are distributed as follows between the domains: psychosocial 37.7%, promotion 22.1%, technology 28.6%, economic 9.1% and environment 2.6%. In turn, enablers are distributed as follows: psychosocial 47.4%, promotion 26.3%, technology 10.5%, economic 14.5% and environment 1.3% (Fig. 4).

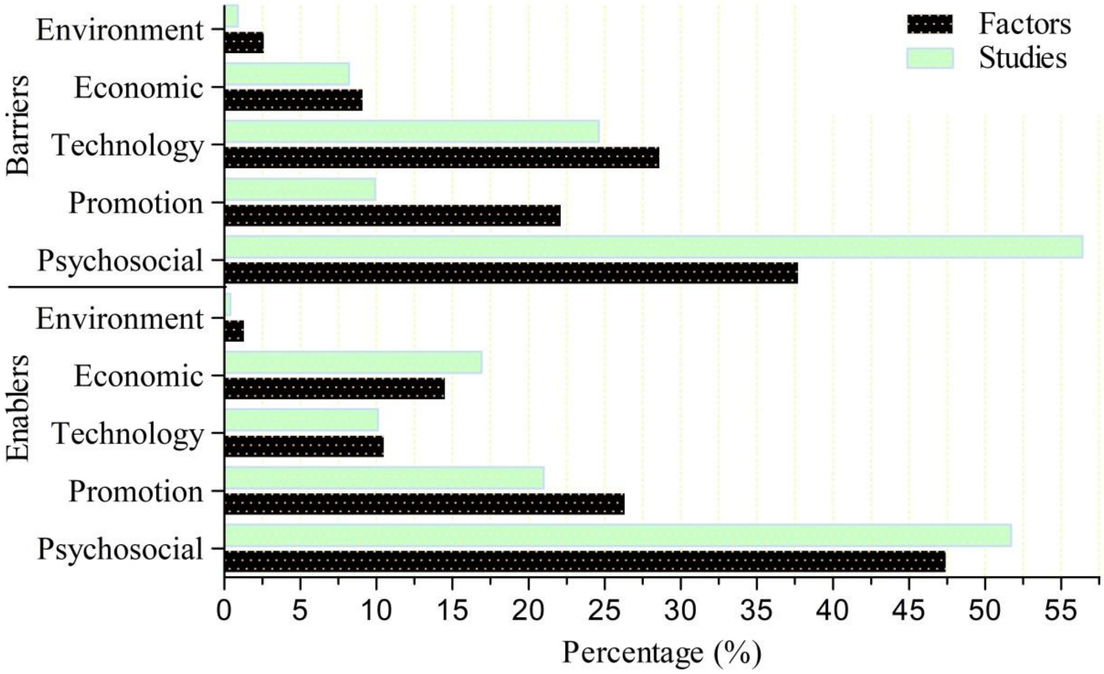


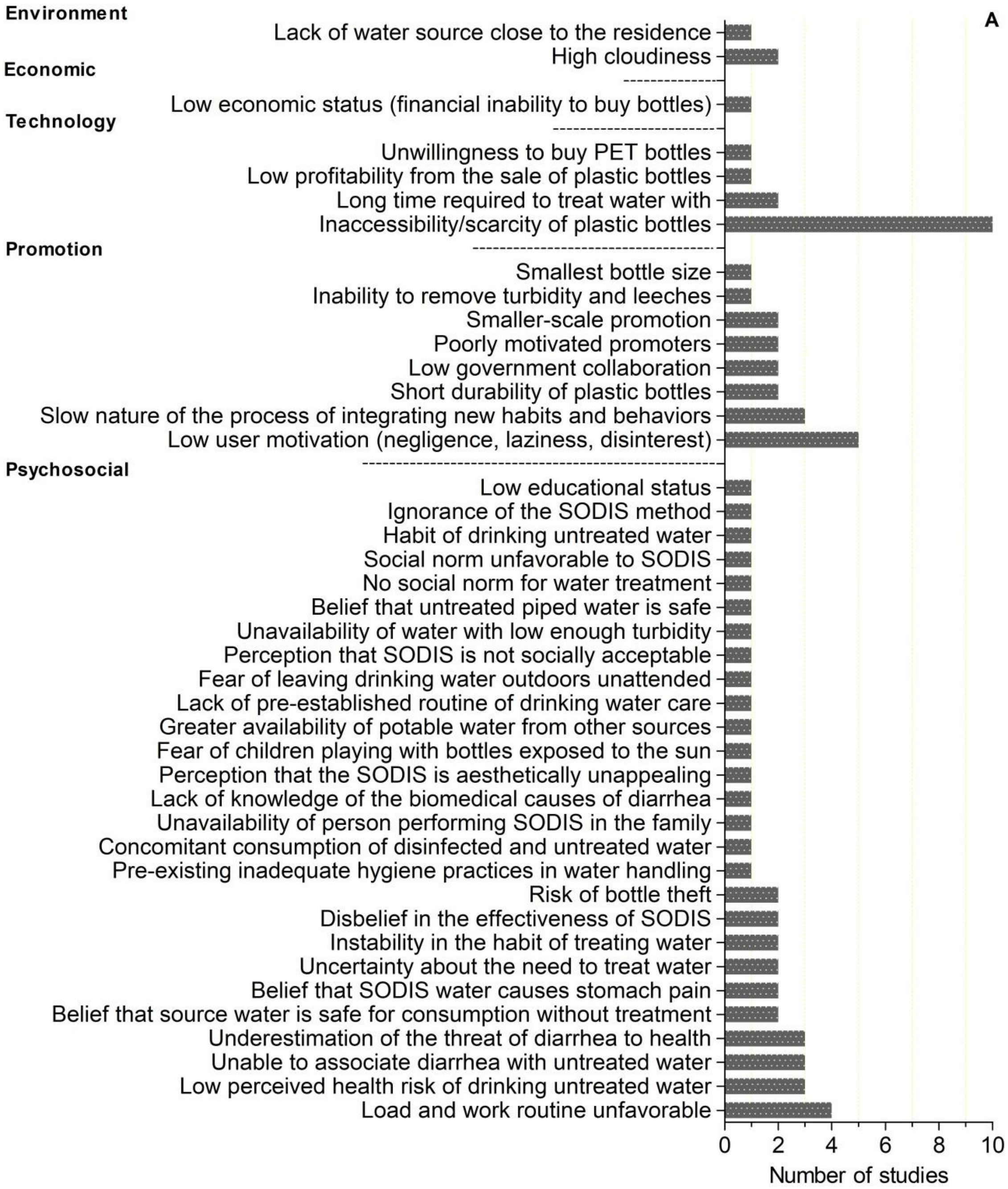
Fig. 4. Distribution of factors (barriers and enablers), and number of studies (evidences) identifying the factors in each of the domains.

Considering the sum of the number of studies that identify each of the barriers or enablers, the following frequency distribution by domain was obtained. Barriers: psychosocial 56.4%, promotion 9.9%, technology 24.6%, economic 8.2% and environment 0.9%. This means that psychosocial, promotional and technological barriers, for example, were reported by 56.4, 9.9 and 24.6% of the reviewed studies. For enablers, the following distribution was obtained: psychosocial 51.7%, promotion 21.0%, technology 10.1%, economic 16.9% and environment 0.4% (Fig. 4). Numbers of studies that identify each of the barrier or enabler (for all HDWT's) per domain are presented in detail in Fig. S1 and S2.

It is clear that the success or failure of HDWT-based interventions to improve drinking water safety is limited, or favored by different factors belonging to the domain, psychosocial, promotion, technology, economic and environment. The psychosocial domain brings together a greater number of factors, as well as evidence that supports these factors, both for barriers and for enablers.

3.2. SODIS

42 barriers and 31 enablers for SODIS-based interventions were identified [26,82,87,90-111], distributed as follows by the different domains. Barriers: psychosocial 64.3%, promotion 11.9%, technology 9.5%, economic 9.5% and environment 4.8%. Enablers: psychosocial 51.6%, promotion 25.8%, technology 9.7%, economic 9.7% and environment 3.2%.



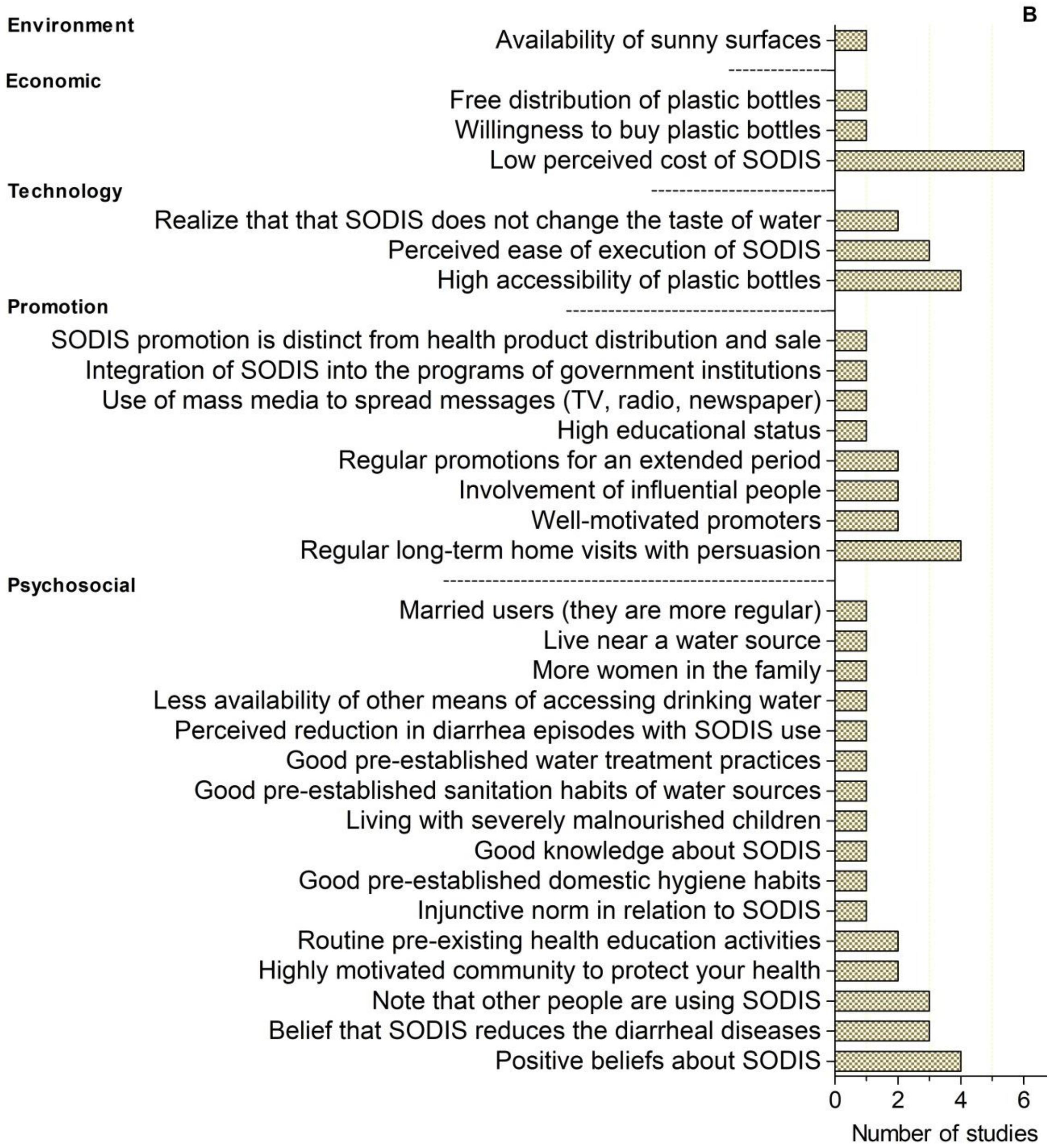


Fig. 5. Barriers (A) and enablers (B) for SODIS-based interventions to improve safety of drinking water at the household level (Details in Table S1).

Among these barriers, the most frequently reported (by ≥ 3 studies) are: Psychosocial - underestimation of the threat of diarrhea to health, inability to associate enteric disease with consumption of untreated water, low perceived health risk of drinking untreated water, and load and work routine unfavorable to the practice of SODIS. Promotion - low user motivation. Economic – inaccessibility ou scarcity of plastic bottles.

Similarly, the enablers mentioned by the highest number of studies (≥ 3) per domain are: Psychosocial – positive beliefs about SODIS, and noticing that other people are using SODIS. Promotion - regular long-term home visits combined with persuasion. Technology - high accessibility of plastic bottles, and perceived ease of execution of SODIS. Economic – perceived low cost of SODIS (Fig. 5).

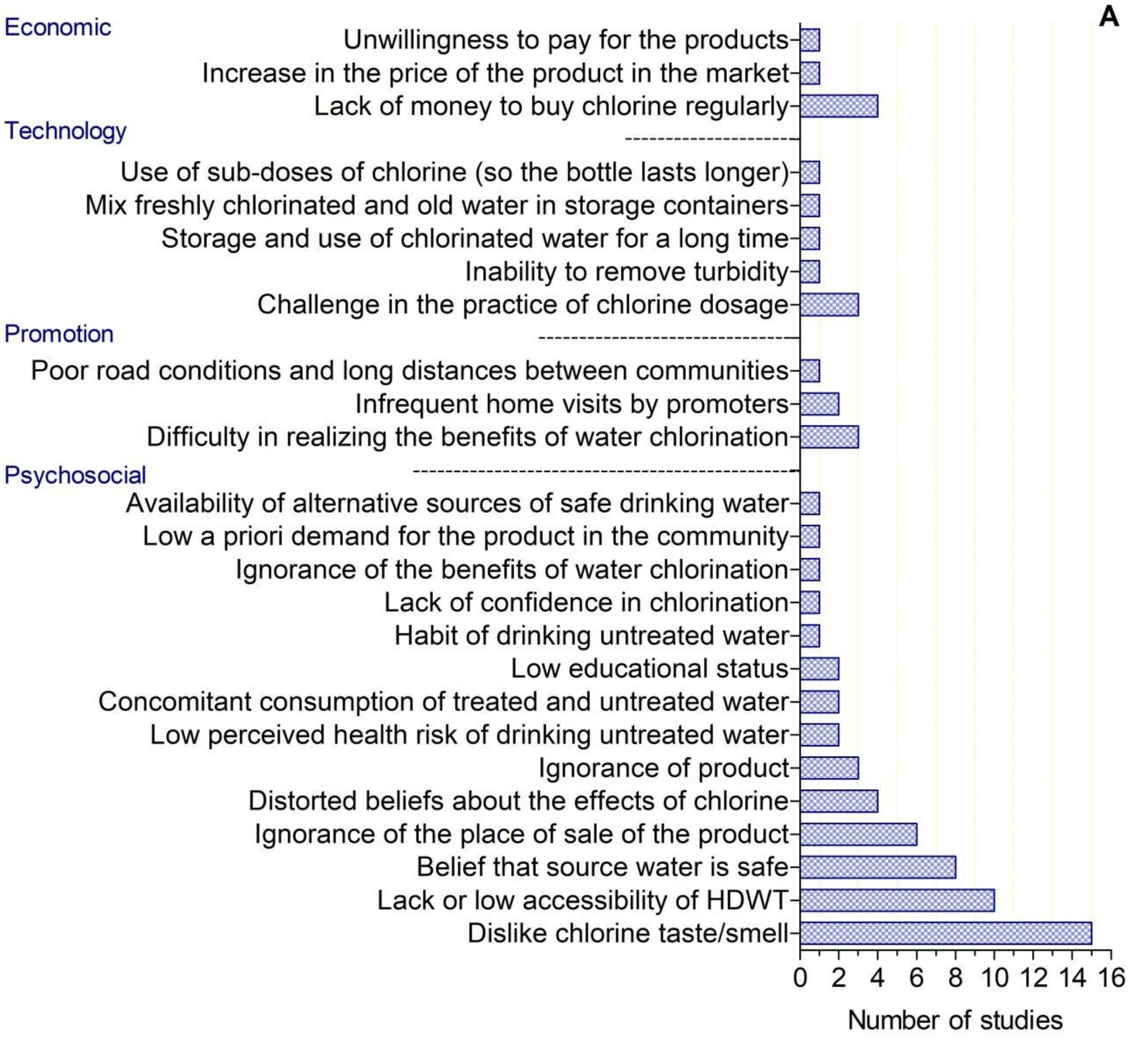
The technological domain barriers identified to SODIS, which include the short lifetime of plastic bottles, smaller bottle sizes, inability to remove turbidity and leeches, long time required to treat water, and the perception that the practice of SODIS is aesthetically unpleasant, can be overcome through improvements in reactors. Using durable high UV transmittance materials like (fortified) glass to build SODIS reactors, which integrate efficient heat absorbers as well as radiation concentrating collectors can increase durability, reduce rejection for aesthetic reasons as well as increase water productivity [12,228]. Devices similar to those described by Magalhães et al. [229] and Farhadi et al. [230] can be built, integrating a filter to remove particulate matter and turbidity, and thus overcome the aforementioned barriers. The barrier of low productivity can also be overcome by using larger reactors [18,244]. Although these improvements may imply a higher initial investment, these more effective and durable devices are more economical in the medium and long term, and will allow overcoming the barrier based on the scarcity of plastic bottles, mainly in rural areas. Other barriers and facilitators are discussed in sections 3.8 – 3.12.

3.3. Chlorination

The Fig. 6 the 25 barriers and 29 enablers identified by studies describing chlorine-based interventions [57,63,97,111-148,242]. Most barriers (56.0%) are in the psychosocial domain, followed by promotion (12%), technology (12%) and economics (12%). No barriers were identified for the environment domain. A similar distribution for enablers across domains was found, such as the following: psychosocial 41.4%, promotion 31.0%, technology 6.9%, economic 17.2% and environment 3.5%.

Among the barriers identified, the following are reported by the largest number (≥ 3) of studies. Psychosocial – belief that source water is safe for consumption without treatment, distorted beliefs about the effects of chlorine, aversion to the taste and smell of chlorinated water, inaccessibility to products, and lack of knowledge of where the product is sold. Promotion - difficulty in realizing the benefits of water chlorination (favored by the episodic character of diarrhea). Technology - challenge in the practice of chlorine dosing. Economic - lack of money to buy chlorine regularly (Fig. 6).

Likewise, the most mentioned enablers are the following. Psychosocial – better knowledge about the need to treat drinking water, and belief in own ability to correctly use the product. Promotion - involvement of individuals trusted by communities in product promotion (e.g. NGO, health professionals, local leaders), concomitant social marketing (reinforcing promoter instructions), distribute or sell chlorine together with safe water storage container, and high frequency of receiving instructions on water chlorination. Finally, for the economic domain – high chlorine accessibility (low price, high availability, free distribution) and willingness to pay for products (Fig. 6).



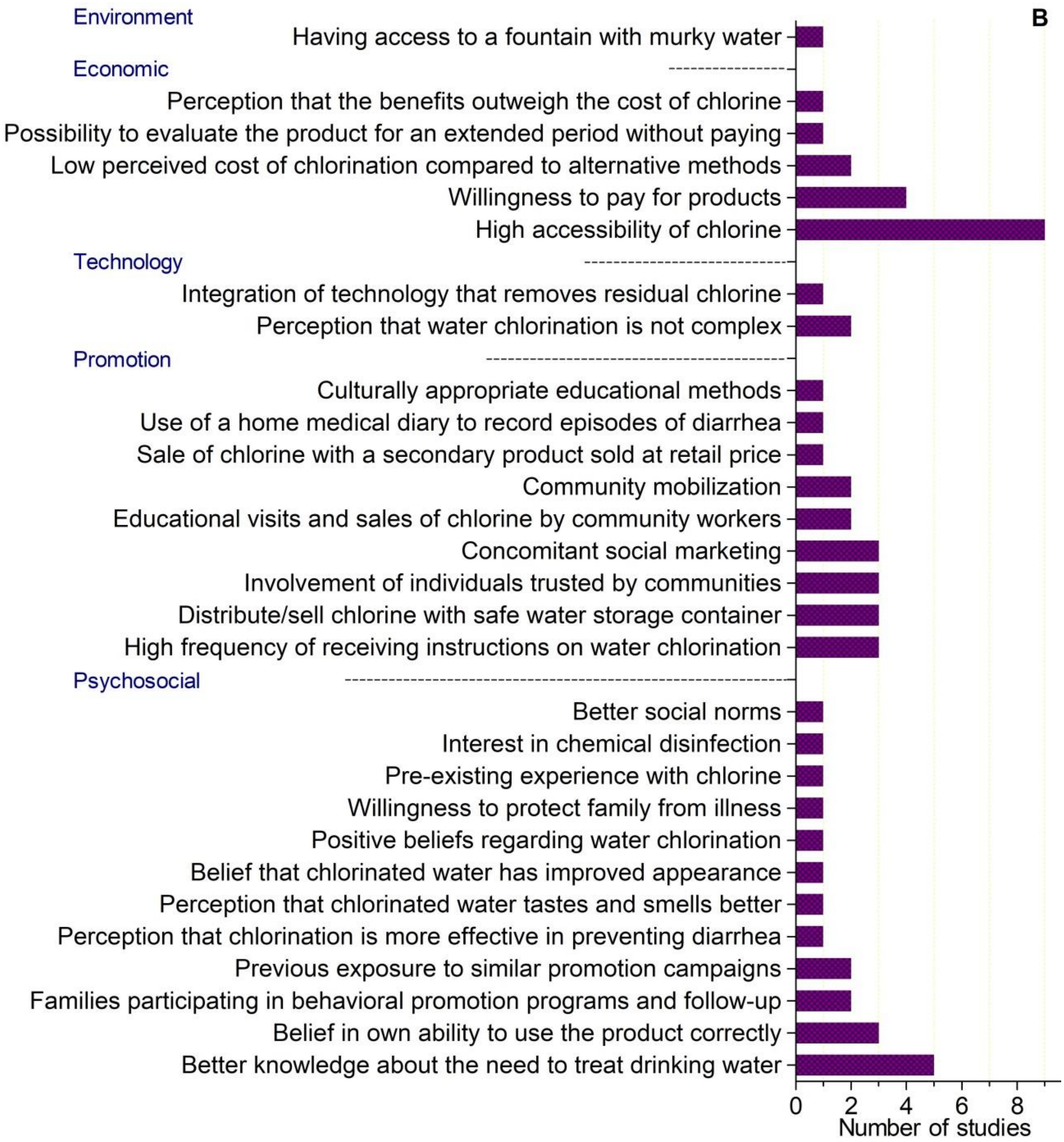


Fig. 6. Barriers (A) and enablers (B) for chlorination-based interventions to improve safety of drinking water at the household level (Details in Table S2)

3.4. Flocculant-disinfectant

Fig. 7 presents all barriers (6) and enablers (11) identified for interventions to improve drinking water safety through the use of flocculant-disinfectant [41,57,71,130,135,136,149-153]. Among the barriers, 50.0% (3/6) are psychosocial, 16.7% (1/6) are in the promotion, and 33.3% (2/6) are in technology domain. Among the enablers, 63.6% (7/11) are psychosocial, 18.2% (2/11) promotion and 18.2% (2/11) are in the technology domain (Fig. 7, Table S3).

The barriers most mentioned (by ≥ 2 studies) are in the psychosocial and Technology domains. Psychosocial: aversion to the taste and smell of treated water. Technology: difficulty in using the product, and perception that the treatment process is time-consuming. On the other hand, the most identified enablers are: ability to correctly perform water treatment with the product, perception of visual improvement in the quality of treated water, and perception that treated water tastes and smells better than untreated, for the psychosocial domain. For the promotion, the most identified enabler is regular and frequent home visits by promoters (community acquaintances), and finally for technology domain, perception that the treatment process is easy and fast, (Fig. 7).

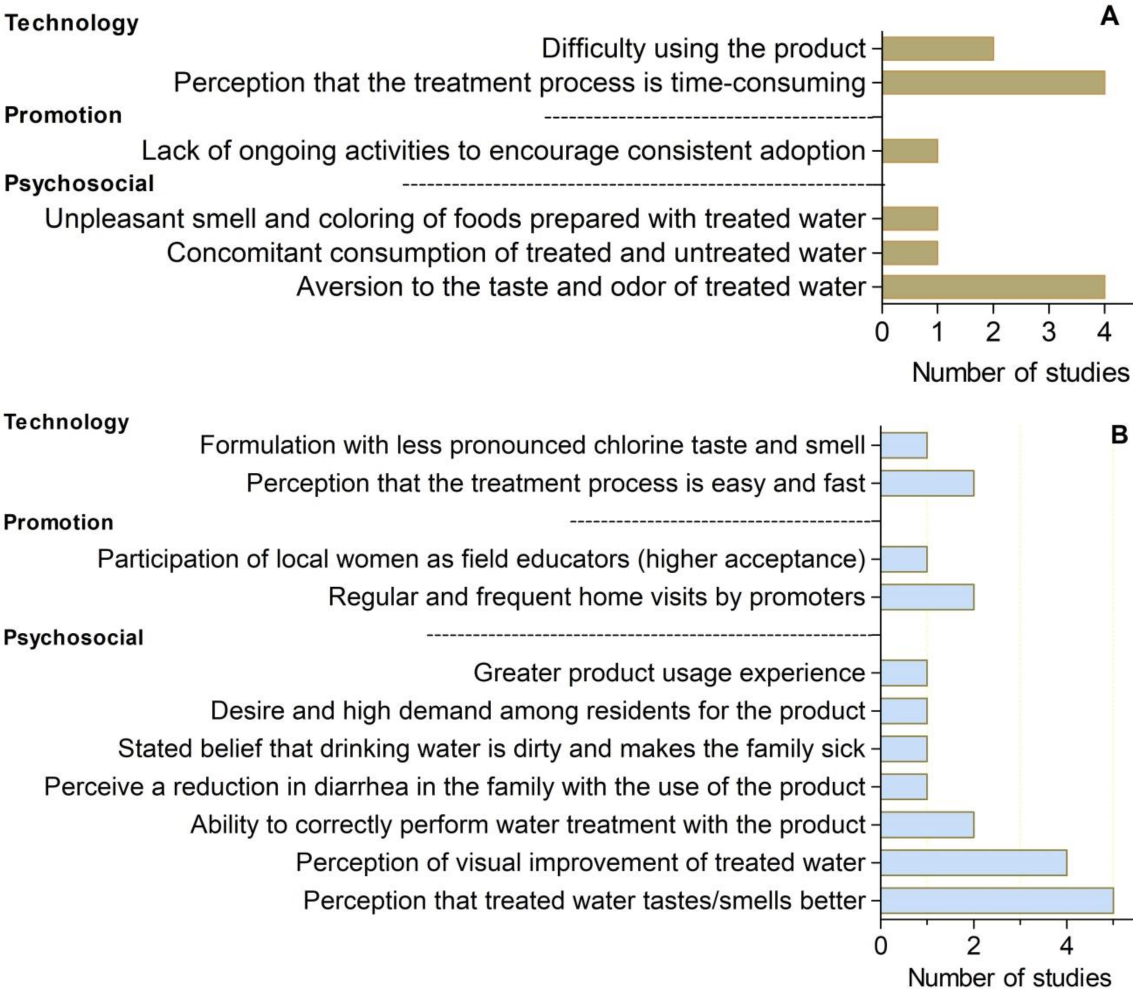
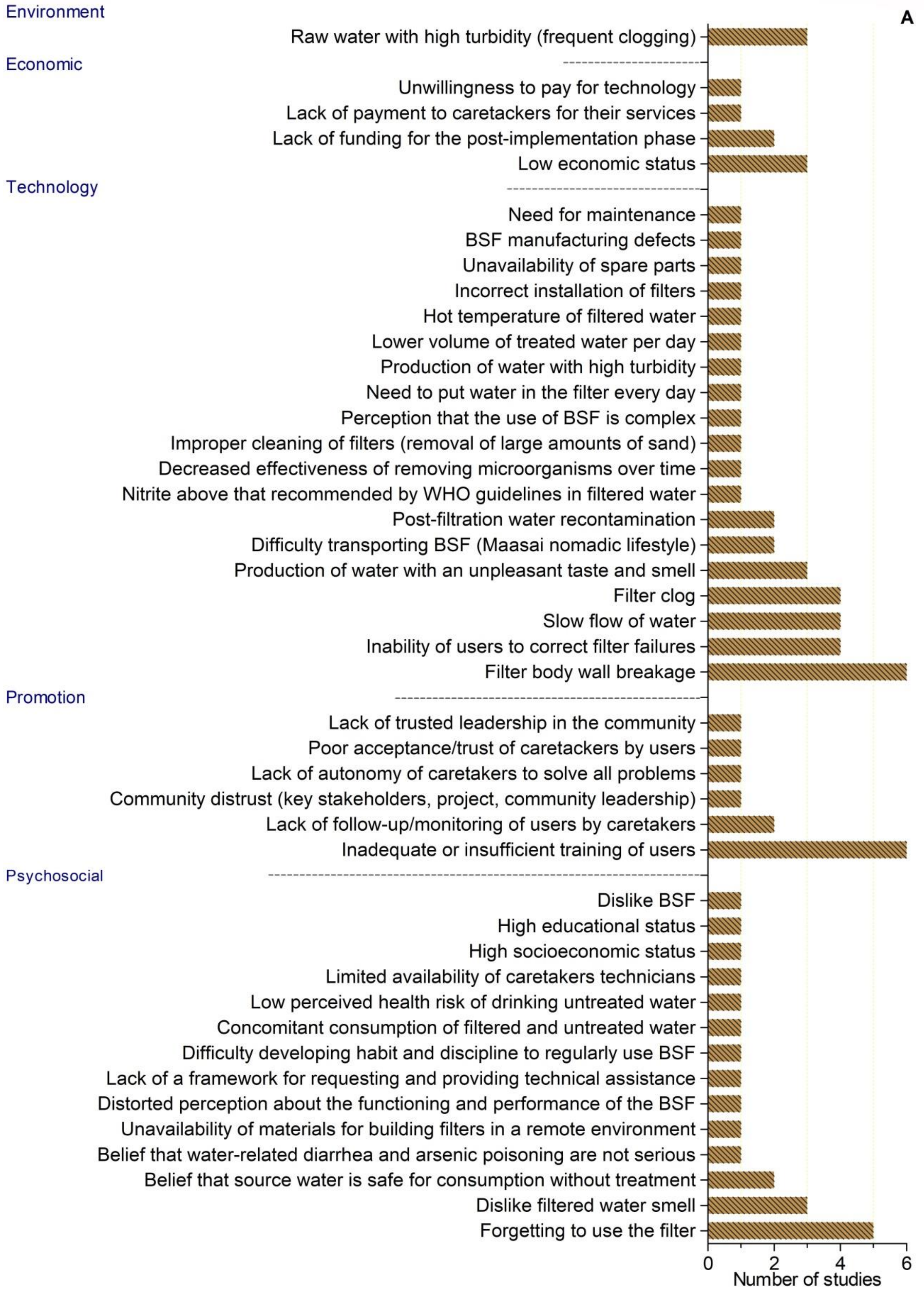


Fig. 7. Barriers (A) and (B) enablers for flocculant-disinfectant-based interventions to improve safety of drinking water at the household level (Details in Table S3).

Key barriers to chlorination that require improvements in technology to overcome include the inability to remove turbidity and the practical challenge of chlorine dosing. The aversion to the smell and taste of treated water is a barrier that chlorination shares with flocculation-disinfection (Fig. 7). The flocculation-disinfection technology helps overcome the aforementioned chlorination barriers. However, the integration of a turbidity removal step such as filtration prior to chlorination will overcome this limitation. The use of chlorine tablets is an alternative chlorination mechanism that allows for a more instinctive and easy dosing of chlorine in the water. However, the diversity of the chemical, microbiological and physical composition of water from different sources makes accurate dosing challenging to ensure the biological and chemical safety of water according to WHO guidelines [30,218]. It is still necessary to develop devices that facilitate the dosing of chlorine solution. The coupling of devices that reduce the concentration of residual free chlorine to tolerable or imperceptible levels of smell and taste (~1.16 mg/L and 1.26 mg/L for NaOCl and NaDCC, respectively) has been shown to be very useful for good acceptance of chlorinated water [144,231]. It is also desirable that these devices also be able to remove the DBPs that can be formed during the treatment of water with chlorine, or flocculant-disinfectant [232]. Filters based on activated carbon and/or graphite-based materials are examples of resources that can be used to build these devices [144,233]. Other barriers and enablers to interventions based on chlorination or flocculating-disinfectant are discussed in sections 3.8 – 3.12.

3.5. BioSand filter

Studies reporting results from BSF-based interventions to improve drinking water quality at the household level revealed 44 barriers and 28 enablers [46,47,56,115,154-172], distributed as follows among the domains. Barriers: psychosocial 31.8%, promotion 13.6%, technology 43.2%, economic 9.1% and environment 2.3%. Enablers: psychosocial 32.1%, promotion 39.3%, technology 14.3%, economic 14.3% and environment 0.0% (Fig. 8, Table S4).


A
Environment
Raw water with high turbidity (frequent clogging)
Economic
Unwillingness to pay for technology
Lack of payment to caretackers for their services
Lack of funding for the post-implementation phase
Low economic status
Technology
Need for maintenance
BSF manufacturing defects
Unavailability of spare parts
Incorrect installation of filters
Hot temperature of filtered water
Lower volume of treated water per day
Production of water with high turbidity
Need to put water in the filter every day
Perception that the use of BSF is complex
Improper cleaning of filters (removal of large amounts of sand)
Decreased effectiveness of removing microorganisms over time
Nitrite above that recommended by WHO guidelines in filtered water
Post-filtration water recontamination
Difficulty transporting BSF (Maasai nomadic lifestyle)
Production of water with an unpleasant taste and smell
Filter clog
Slow flow of water
Inability of users to correct filter failures
Filter body wall breakage
Promotion
Lack of trusted leadership in the community
Poor acceptance/trust of caretakers by users
Lack of autonomy of caretakers to solve all problems
Community distrust (key stakeholders, project, community leadership)
Lack of follow-up/monitoring of users by caretakers
Inadequate or insufficient training of users
Psychosocial
Dislike BSF
High educational status
High socioeconomic status
Limited availability of caretakers technicians
Low perceived health risk of drinking untreated water
Concomitant consumption of filtered and untreated water
Difficulty developing habit and discipline to regularly use BSF
Lack of a framework for requesting and providing technical assistance
Distorted perception about the functioning and performance of the BSF
Unavailability of materials for building filters in a remote environment
Belief that water-related diarrhea and arsenic poisoning are not serious
Belief that source water is safe for consumption without treatment
Dislike filtered water smell
Forgetting to use the filter
0
2
4
6
Number of studies

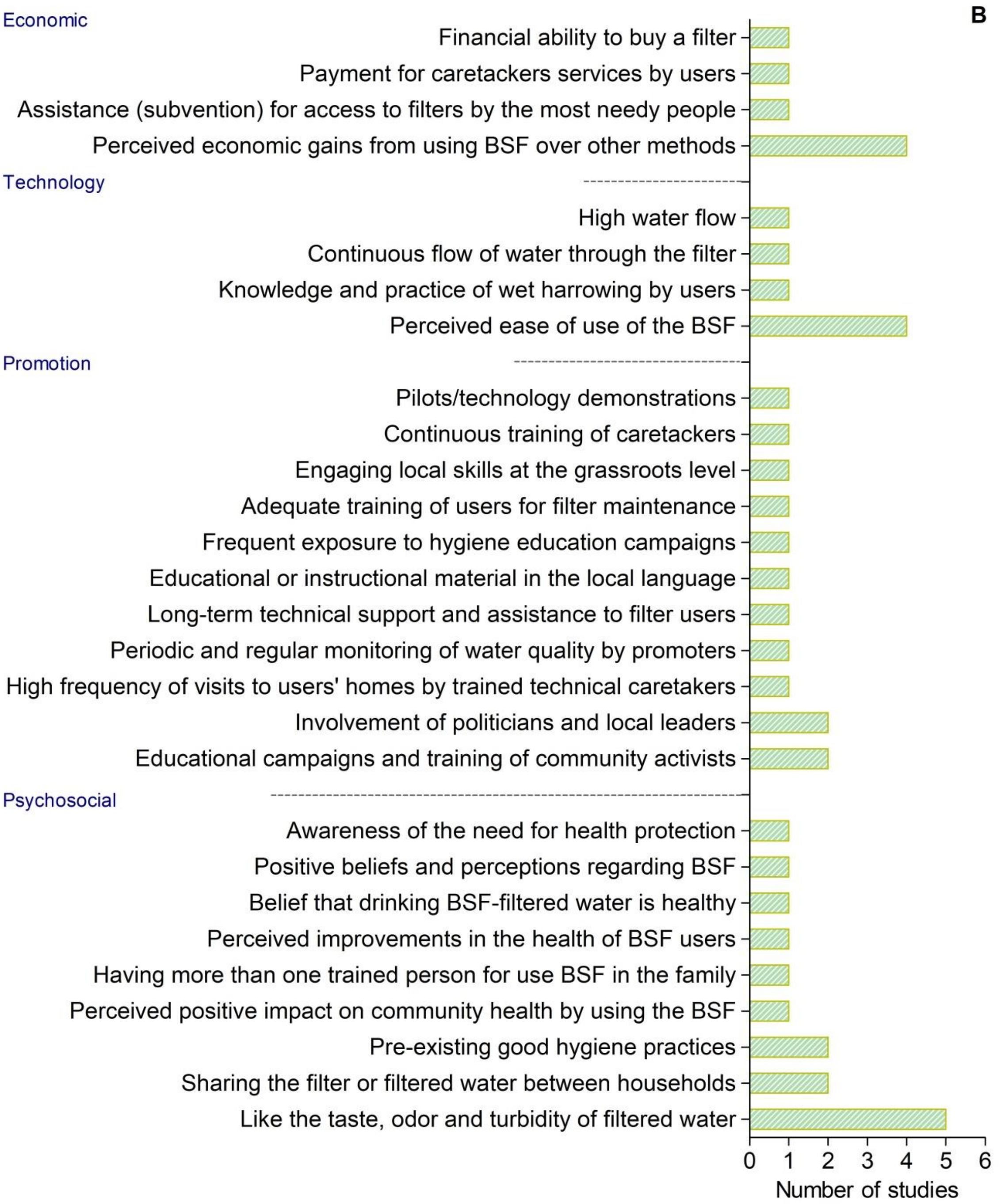


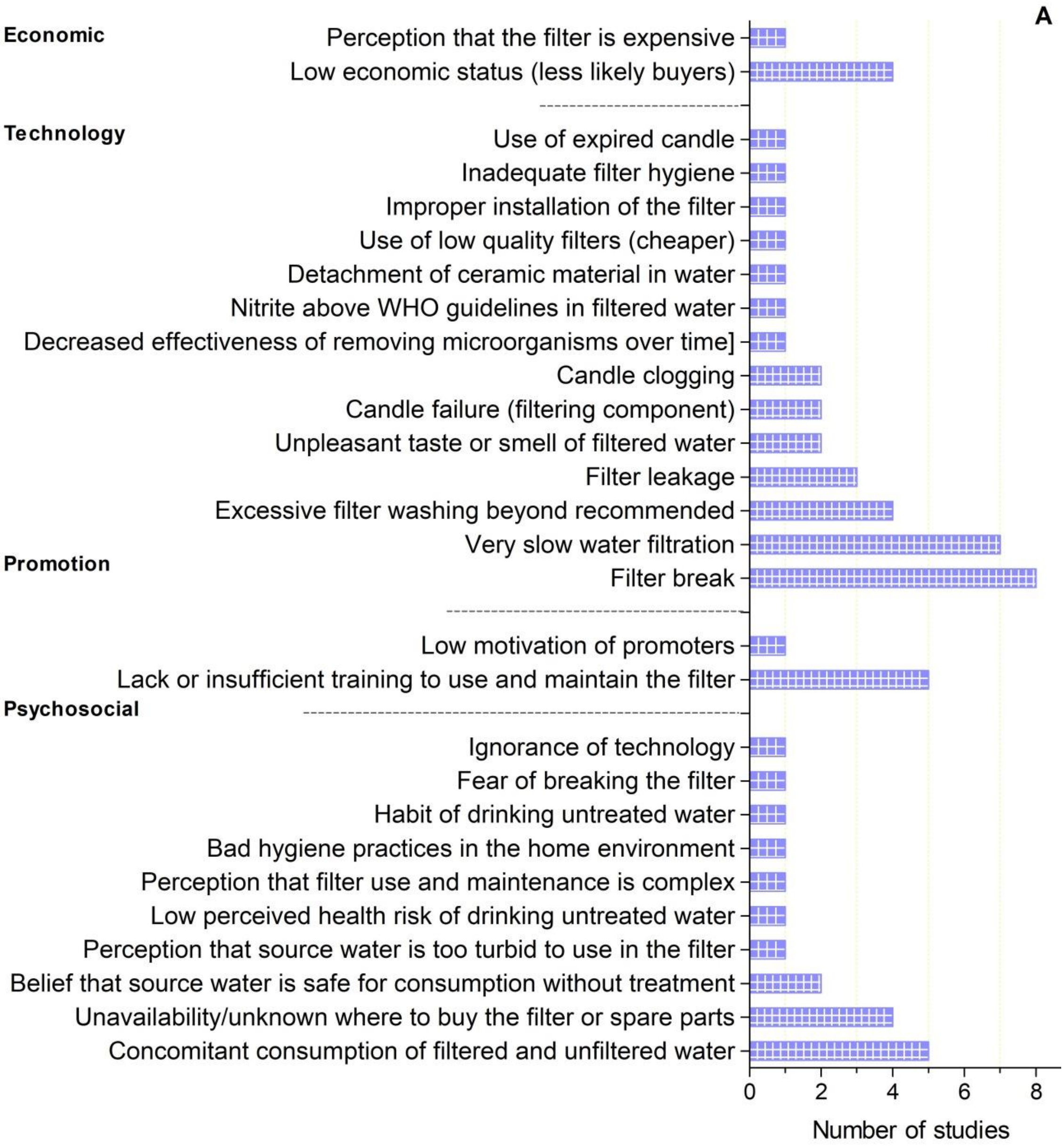
Fig. 8. Barriers (A) and enablers (B) for BioSand filter-based interventions to improve safety of drinking water at the household level (Detaisls in Table S4).

The most frequently reported barriers (by ≥ 3 studies) are as follows: Psychosocial – dislike filtered water smell. Promotion - inadequate or insufficient training of users. Technology - inability of users to correct filter failures, producing water with an unpleasant taste and smell, breakage of the filter body wall, slow flow of water, and filter clogging. Low economic status, and raw water with high turbidity (frequent clogging of the filter) are the most frequently identified barriers for the Economic and environmental domains, respectively. On the other hand, the most frequently identified enablers (≥ 3 studies) fall into the psychosocial domain (satisfaction with the taste, odor and turbidity of filtered water in relation to raw water), Technology domain (perceived ease of use of the BSF), and Economic domain (perceived economic gains from using BSF compared to other methods (associated with long-term sustainability of use)), as shown in Fig. 8.

Among technology-related barriers, one of the most frequently reported to BSF is low daily water productivity resulting from reduced water flow and/or filter clogging. Although this problem can be overcome by properly training the user to perform filter maintenance, which consists of removing / shaking <1 cm or replacing 5 cm of the top layer of filter media [234], or through wet harrowing [46]. However, the addition of a layer of washable filtering material (e.g. non-woven blankets) over the filtering medium prevents or reduces the accumulation of impurities in the filtering medium, prolonging the filter's operation and improving its performance [235]. The reduction in the effectiveness of the BSF in removing microorganisms, especially after maintenance, can be compensated by integrating a post-filtration disinfection step, for example, SODIS [236] or chlorination. The barrier related to filter body wall breakage can be overcome by building plastic BSF, which are lighter and less brittle than concrete BSF [215,216]. Improvements to increase the effectiveness of microbiological removal of BSF need to consider the integration of different components currently used in water treatment, such as zeolite, colloidal silver, clay, activated carbon, to overcome other limitations, including, the inability to remove all microorganisms and the bad smell of filtered water [237,238]. Other barriers and enablers are discussed in sections 3.8 – 3.12.

3.6. Ceramic water filter

Lists of 29 barriers and 35 enablers identified for CWF-based interventions are presented in Fig. 9 and Table S5. The distribution of barriers in the different domains is as follows: psychosocial 37.9%, promotion 6.9%, technology 48.3%, economic 6.9% and environment 0.0%. In turn, the enablers are distributed as follows: psychosocial 57.1%, promotion 14.3%, technology 11.4%, economic 11.4% and environment 5.7% [52,54,55,57-59,61,157,164,172-185].


A
Economic
Perception that the filter is expensive
Low economic status (less likely buyers)
Technology
Use of expired candle
Inadequate filter hygiene
Improper installation of the filter
Use of low quality filters (cheaper)
Detachment of ceramic material in water
Nitrite above WHO guidelines in filtered water
Decreased effectiveness of removing microorganisms over time]
Candle clogging
Candle failure (filtering component)
Unpleasant taste or smell of filtered water
Filter leakage
Excessive filter washing beyond recommended
Very slow water filtration
Filter break
Promotion
Low motivation of promoters
Lack or insufficient training to use and maintain the filter
Psychosocial
Ignorance of technology
Fear of breaking the filter
Habit of drinking untreated water
Bad hygiene practices in the home environment
Perception that filter use and maintenance is complex
Low perceived health risk of drinking untreated water
Perception that source water is too turbid to use in the filter
Belief that source water is safe for consumption without treatment
Unavailability/unknown where to buy the filter or spare parts
Concomitant consumption of filtered and unfiltered water
0
2
4
6
8
Number of studies

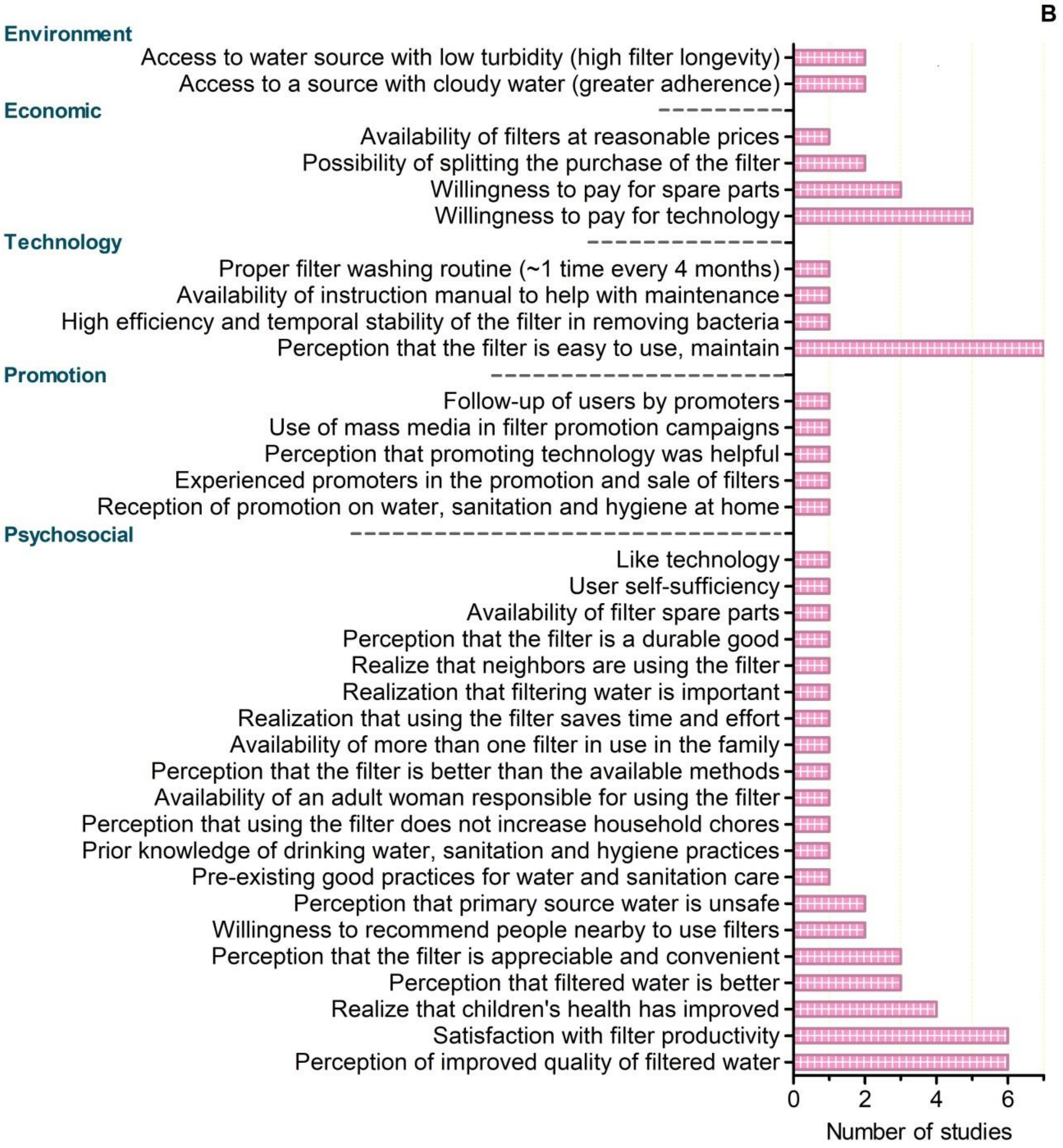


Fig. 9. Barriers and enablers for ceramic water filter-based interventions to improve safety of drinking water at the household level (Details in Table S5).

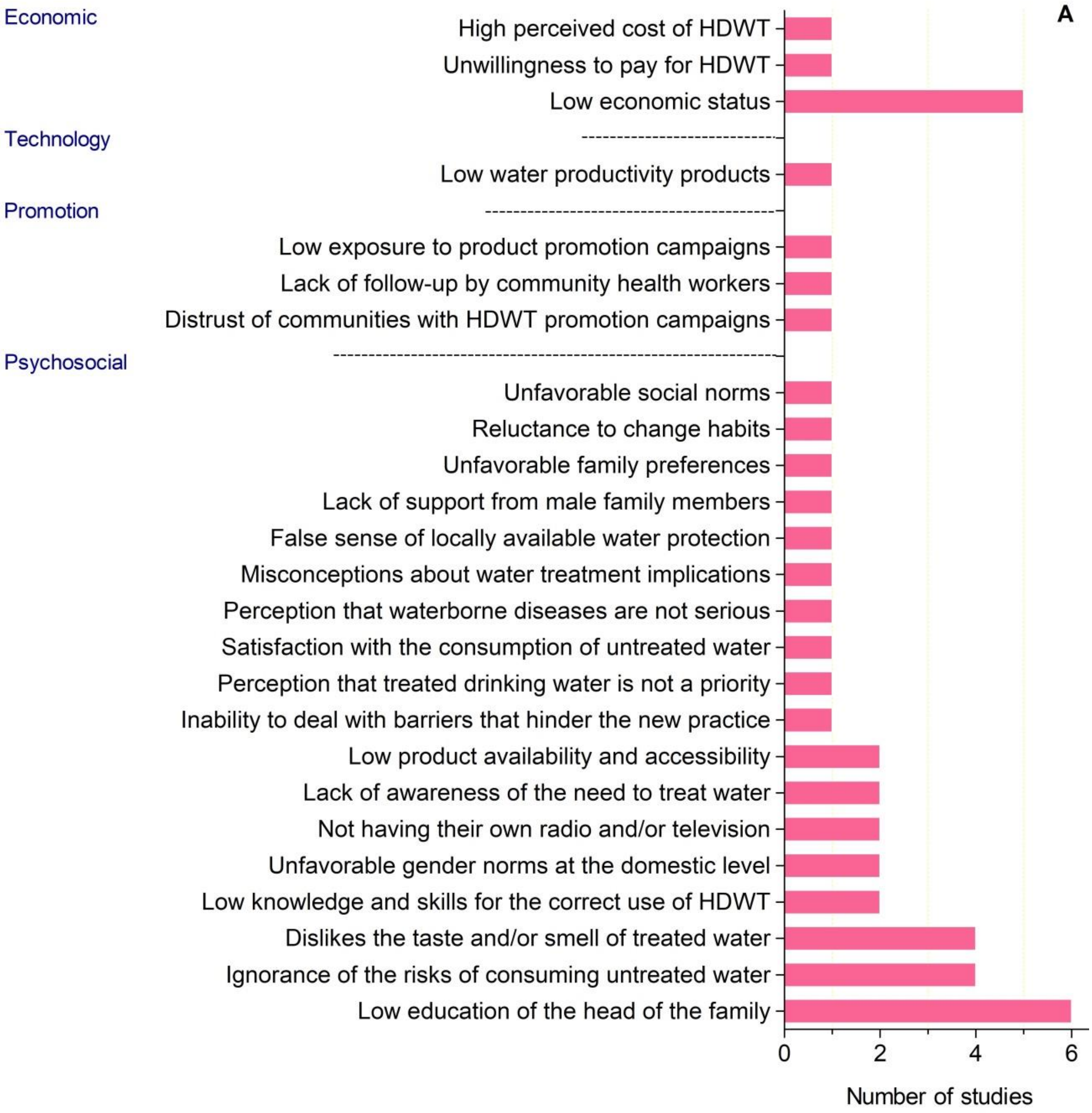
The most mentioned barriers (≥ 3 studies) per domain are: psychosocial - unavailability or lack of knowledge of where to buy the filter or spare parts, and concomitant consumption of filtered and unfiltered water. Promotion - lack or insufficient training to use and maintain the filter. Technology - excessive filter washing beyond recommended, filter breakage, filter leakage, and very slow water filtration. Economic - low economic status. On the other hand, the most frequently identified enablers (≥ 3 studies) are: psychosocial - perception that the filter is appreciable and convenient, perception that filtered water is better than treated with other methods, perception of improved quality of filtered water, satisfaction with filter productivity, and realize that children's health has improved. Technology - perception that the filter is easy to use and maintain. Economic - willingness to pay for technology (at a sustainable price), and willingness to pay for spare parts (Fig. 9).

Low daily water productivity per CWF resulting from slow filtration as well as filter clogging is one of the reported barriers that technological improvements can overcome. Although the challenge of increasing water flow without compromising the effectiveness of removing microorganisms remains [51,239], the integration of step of removal or reduction of water turbidity, before filtration, can in part prolong the operating time and performance of the CWF. Efforts to overcome these limitations should consider pre-filtration flocculation [240], as well as two-step filtration, or the addition of a permeable, removable and washable material to the filter surface covering, to avoid the incrustation of particulate or colloidal material in the pores of the filter. Advances currently documented, which include the addition of 25-30% activated carbon (along with active agents) into the clay used to build CWF, should also be considered for increased productivity, robustness, durability, ability to remove chemical and microbial contaminants [49]. The inclusion of fortifying additives to make the filter wall less brittle is also necessary to overcome the limitation based on filter wall breakage. The development of disc-shaped CWF, with short/medium duration of use, capable of being restored (perhaps by burning) and later reused, would be an advance that would contribute to overcoming many of the barriers listed in the technological domain. Other barriers and enablers are discussed in sections 3.8 – 3.12.

3.7. Technologies for household drinking water treatment in general

The barriers and enablers identified by studies that focused on HDWT in general are presented in Fig. 10 and Table S6. 25 barriers and 23 enablers were identified, distributed as follows by different domains. Barriers: psychosocial 72.0%, promotion 12.0%, technology 4.0%, economic 12.0% and environment 0.0%. Enablers: psychosocial 60.9%, promotion 17.4%, technology 13.0%, economic 8.7% and environment 0.0% [130,186-202].

The most reported barriers (≥ 2 studies) per domain are: Psychosocial - ignorance of the risks of consuming untreated water for health, and lack of awareness of the need to treat water, unfavorable gender norms, low education of the head of the family, low product availability and accessibility, low knowledge and skills for the correct use of HDWT, and dislikes the taste and/or smell of treated water. Low Economic status is the most frequently mentioned barrier to the Economic domain. Among the different enablers listed, previous experience with HDWT, and belief that drinking untreated water causes diarrhea, are the most frequently reported for the psychosocial domain (Fig. 10).



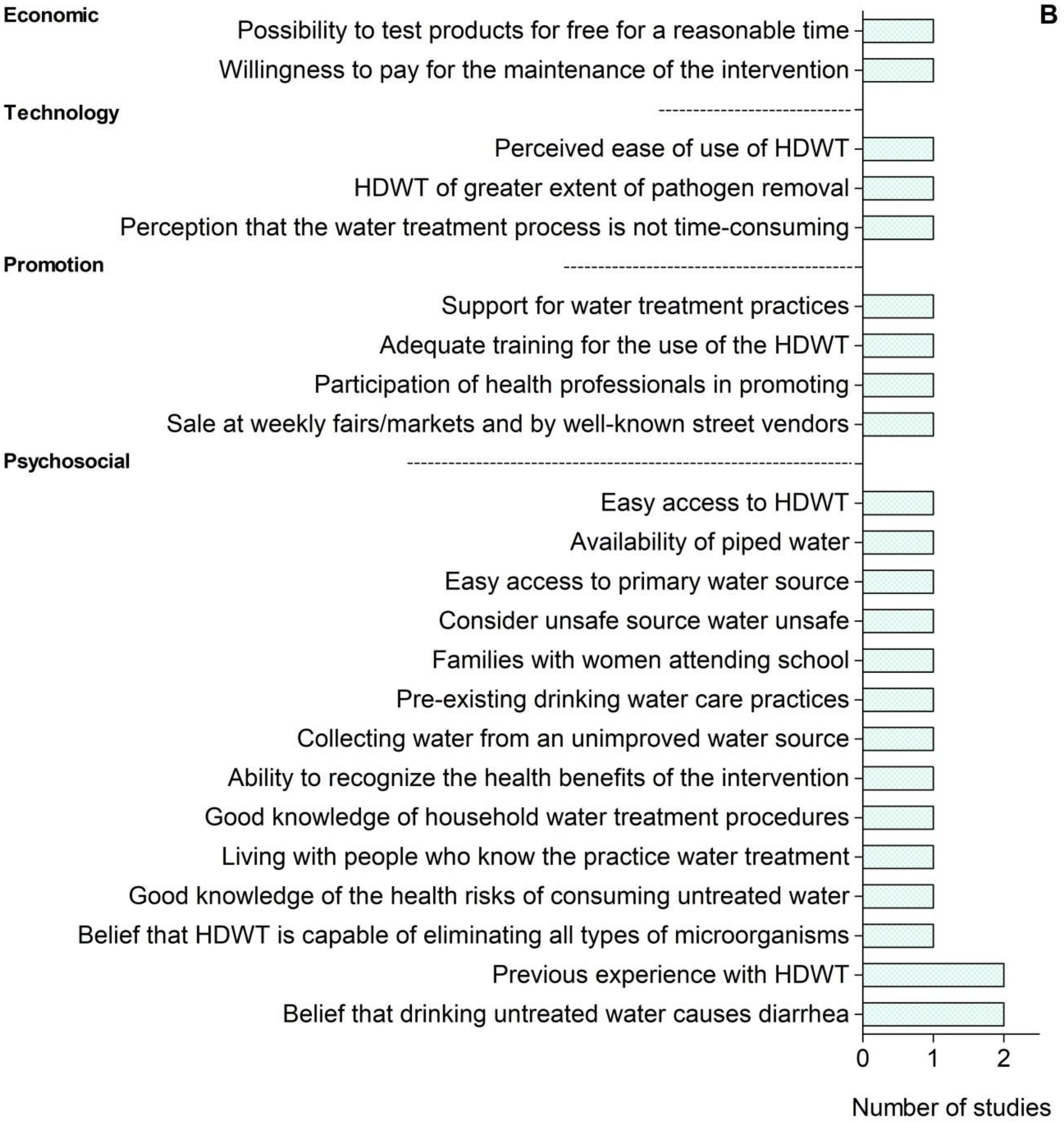


Fig. 10. Barriers and facilitators for interventions based on household drinking water treatment technologies in general (Details in Table S6).

On the other hand, barriers and enablers for HDWT-based interventions identified based on the opinion and understanding of different professionals with experience in household water treatment and safe storage practices (manufacturing, implementation, sales, UN agency, academia, government and others) are presented in Fig. 11 [85].

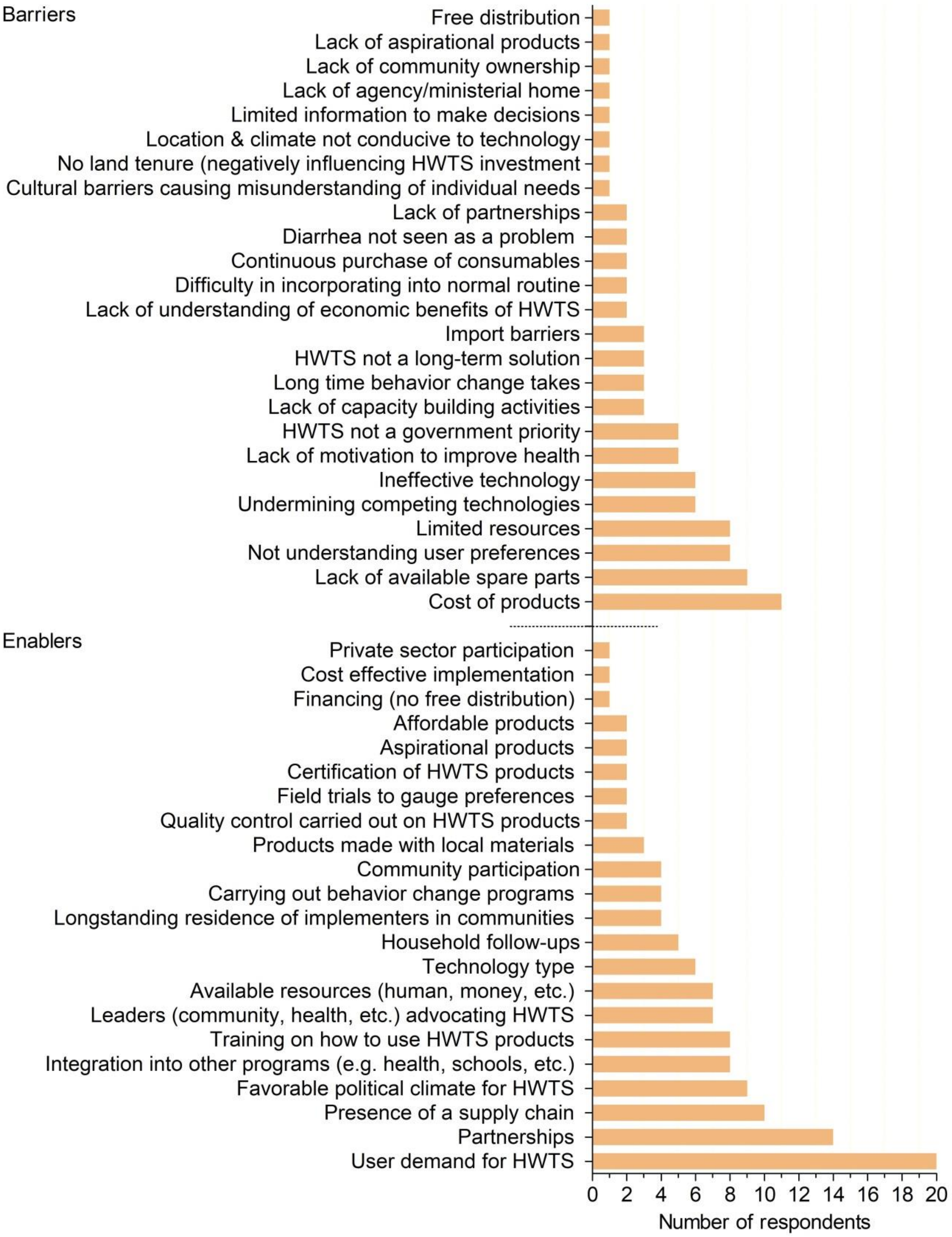


Fig. 11. Barriers and enablers for interventions based on household drinking water treatment technologies (HDWT) in the opinion of professionals with experience working with HDWT use practices.

3.8. All domains and factors are important

Although domains differ in the amount of identified barriers and enablers, either globally or specifically for each HDWT (Fig. 5–11), there is no evidence to suggest that any domain is more influential than another. It is important to note that no barriers or enablers were identified for the environment domain for chemical water treatment technologies, namely chlorination and flocculation-disinfection (Fig. 6 and 7). The absence of any factor (barrier and/or enabler) identified in at least one domain was also verified in technologies such as BSF and CWF (Fig. 8 and 9). However, these results do not indicate that these domains interfere less in the success or failure of interventions aimed at combating waterborne diseases through HDWT. The iron content or the turbidity of the raw water to be treated with chlorine or flocculant-disinfectant are examples of environmental factors that interfere with the residual free chlorine levels, which need to be considered to determine the initial dose of chlorine, as well as the duration of its protective effect [218,219,220].

Each of the different barriers and enablers identified differ in the amount of evidence supporting them across the domain. However, while these findings show how common a certain limiting or enabling factor can be, for different technologies and contexts, they do not suggest that one factor is more influential than the other. Thus, except for some factors that are specific to the technology, such as “the availability of abundant insulation” and “perception of insecurity in leaving HDWT devices outdoors (fearing poisoning or theft of bottles)” which is a specific enabler and barrier for SODIS, it is wise that all HDWT-based interventions consider all factors listed during planning and baseline study [85].

The identified and listed barriers and enablers impact HDWT-based interventions, interfering with different performance metrics, including initial adoption of HDWT, regularity of use, and sustained use, as shown in Table S7.

3.9. Initial adoption of HDWT

The decision to try HDWT use is influenced by different factors described by the RANAS model, namely, risk, attitudes, norms and skills [243]. Almost all of the barriers and enablers listed as interfering factors in the initial adoption of THB are classified as risk factors, attitudes, norms and skills. Thus, the massification of the initial adoption of HDWT depends on the establishment of sufficiently robust cognitive changes about the real health risk and the fear of consuming untreated water [202]. This change needs to be able to build positive beliefs about water treatment, rebuilding favorable norms (by deconstructing unfavorable ones) and thus inducing the development of necessary skills [243]. For this, the listed barriers need to be considered and overcome, and the enablers presented need to be identified and/or created and explored to massify the initial adoption of HDWT.

Overall, the highest rates of early adoption of HDWT were reported in interventions that in addition to providing education, carrying out promotion and training, also donated or promotionally sold the technology, both for SODIS [26,205], chlorination [209,210], flocculation-disinfection [150,71], BSF [161,215] and CWF [58,61]. This conclusive understanding is corroborated by the result, which shows that the following barriers "belief that untreated water is safe for consumption" and "low socioeconomic status" are factors that gather a high number of supporting evidence (Fig. S1). It also agrees with the findings of Fisher et al. [221] who observed that behavior related to water tended to follow the knowledge acquired through the education program, except in cases where personal financial expenses were necessary.

3.10. Regular use

Although the regularity of HDWT use depends mainly on the factors that impact initial adoption [83,107], it is mainly determined by the following factors described by the RANAS model, attitudes, norms and skills [222,243], and the corresponding barriers and enablers are listed in the results (Table S7). The following barriers, lack of water source close to the residence, load and work routine unfavorable to use HDWT, long time needed to treat water, need to put water in the HDWT device every day, and difficulty developing habit and discipline, stand out among the factors that hinder the regular use of all HDWT. The difficulty realizing the benefits of water, treatment, concomitant consumption of treated and untreated water, lack of ongoing activities to encourage consistent adoption of the intervention, infrequent home visits by promoters, and low acceptance/trust of caretakers by users, are equally important identified barriers. The aversion to taste and treated water is one of the most important factors that hinder the regular treatment of water, mainly with chlorine and flocculant-disinfectant, although it has also been reported for BSF. The perceived insecurity of leaving HDWT devices outdoors and unfavorable weather conditions (high cloud cover) are specific barriers to the regular use of SODIS. Actions for changes and establishment of behaviors for the regular use of HDWT need to consider and seek to overcome each of the identified barriers. Ways of overcoming these barriers primarily include identifying and/or creating and exploiting the corresponding enablers also listed (Fig. 5-11, Table S1-7).

3.11. Sustained use

Sustained use of HDWT is, in practice, regular use maintained over time, and depends on prior success in inducing risk perception, developing attitudes, norms and skills that, together, lead to desired water-related behavior, which will ultimately result in regular use [83]. Sustained use mainly depends on the development of self-regulation [243], and the corresponding barriers and enablers are listed in Table S7. Each of the barriers and enablers is critical to the regular use of HDWT and needs to be considered by planners and implementers of interventions. Actions need to aim at continuously strengthening favorable social norms, making obvious the need and benefits of maintaining desired water-related behavior [87,100], as well as strengthening accessibility, self-efficacy and self-regulation [82].

Failure of the intervention to significantly improve the quality of water consumed due to several factors, which include concurrent consumption of treated and untreated water, post-treatment water recontamination, reduced effectiveness in removing microorganisms (poor quality HDWT, poor stability) and the misuse of HDWT (dosage, expiry date, etc.), can lead to a perception that the use of HDWT is not beneficial, due to the continuation of frequent reports of diarrhea. However, it is important to highlight that less effective devices (e.g., remove fewer pathogens) contribute to substantial reductions in the risk of diarrheal disease if compensated with higher adherence (e.g., better usability/better adoption) than more effective but lower usability technologies [81].

Ongoing activities, including follow-up by motivated and self-sufficient caretakers, combined with the establishment of mechanisms for requesting and assisting users, induce the maintenance of regularity in the use of HDWT over time [56,150,163,223]. The use of certified technologies, with better quality (performance, durability, robustness, etc.), greater productivity and stability, more accessible, and easier and faster to use, is recommended, as it allows overcoming a significant number of the listed barriers to the sustained use [85].

3.12. Considerations for educational and promotional campaigns

A total of 17 barriers associated with the failure of education and promotion campaigns were identified. Among them are the following: lack or insufficient training to use and maintain the HDWT, low motivated users, difficulty realizing the benefits of water treatment, perception that the use and/or maintenance of the HDWT is complex, infrequent home visits by promoters, community distrust of HDWT technology promoters and leadership, poorly motivated promoters, and difficulty transporting the HDWT technology, are the ones that gather the highest numbers of supporting evidence (7, 5, 3, 2, 2, 2, and 2) respectively (Fig. S1). These findings suggest that among several objectives, promotion activities need to ensure that users have sufficient training to correctly use and maintain the HDWT. Since many of the identified barriers originate from this barrier, for example, post-treatment water recontamination, improper HDWT use (dosage, expiration date, excessive washing) and sanitization, and perception that the use and/or maintenance of the HDWT is complex.

It is also essential and very beneficial for promoters to be highly motivated, committed and, if possible, experienced people, so that they can successfully motivate users, as these qualifiers are important predictors of the success of promotion activities [105,110,178]. It has been suggested that HDWT experimenter-users revert to old habits when the reasons for continuing to practice household drinking water treatment are not obvious [87]. Thus, it is important to establish mechanisms that help users realize the benefits of household water treatment. The use of health diaries to record episodes of diarrhea [140], demonstrations of microbiological water analysis results [99,202], as well as talking about the gains, from household water treatment [224,225], are examples of practices that can be explored to reinforce desired water-related behavior. None of these practices mentioned can be properly carried out without the implementation of a routine of frequent and prolonged home visits by the promoters. In turn, home visits and interactions with communities will only have the desired effect if the people involved manage to gain the trust of communities. A shorter way to gain trust and ensure community engagement is to involve in intervention planning, education and advocacy activities, people and/or institutions who are influential and trusted by communities, including local leaders, local residents with an emphasis on women, health professionals, teachers, government officials, NGO and universities [71,82,226,227]. Large-scale promotion and outreach campaigns (instead of promotions confined to geographic “pockets”), using mass media (TV, radio, newspapers, social networks, etc.) inspire more trust in communities towards promoters, making them more likely to value and experience HDWT [82,105]. Logistical barriers, with a focus on those related to technological factors, need to be properly planned taking into account the challenges of the context, always bearing in mind the sustainability of the intervention [73,86]. Education and promotion campaigns should be based on, and also aim at, the development of self-sufficiency (material, technological and financial) of local promoters, so that even after the end of long-term promotion activities and the consequent departure of non-resident promoters, post-implementation promotion activities can continue and expand [56].

3.13. HDWT technology delivery strategies

The HDWT delivery strategies used in interventions based on SODIS [26,95,103,106,108,203-207], Chlorination [10,41,63,131,138,140,143,152,208-212], Flocculant-disinfectant [10,41,71,150,152], BSF [46,48,161,169,213-216], and CWF [48,55,58,59,60,61,177,182,217] essentially aimed at: (1) promoting education and HDWT in communities, (2) training users on the use and maintenance of HDWT, and providing HDWT technology, through (3) donation or (4) promotional sales (Details in Table S8). They also aimed to (5) provide a secure storage container free of charge, (6) provide technical assistance, as well as (7) measure the impact of the intervention on diarrheal prevalence, as shown in Table S8. The operationalization of these objectives occurred in different ways.

The promotion of education and HDWT was carried out through awareness campaigns about the risk of waterborne diseases, the need to consume treated drinking water, and the importance of HDWT. To this end, several resources were used, including mass media, lectures, games, interactive images, drama, pamphlets, posters, calendars, shows, murals, videos, door to door campaign, street calls, with or without involvement of local promoters, health professionals, politicians, local leaders, NGO and other influential people. Training to use technology took place through demonstrations and provision of illustrated injunctive texts (with accessible language) in lectures, workshops and door-to-door campaigns. The supply of technology was characterized by the offer and installation (if necessary) of the technology to interested parties, free of charge or through sale at discounted prices. Technical assistance was characterized by routine home visits by promoters who, in addition to helping users with any problems faced in the use of technology, encouraged its correct and sustained use. Measuring the impact of the intervention on the prevalence of diarrheal disease consisted of training users to record diarrheal episodes by completing a clinical diary (before and/or after adopting the HDWT technology).

The results of the analysis of the interaction between the variables 'Technology delivery strategy', 'Time', 'Compliance' and 'Diarrheal risk reduction', based on a series of OLS hierarchical regression models in the Table 1. Because we performed several regression models in such analysis, we opted not to report all non-significant estimations. This explains the reason why many fields are blank in Table 1. In addition, some variables like Time and Compliance have “no effect” written. In practice, they did not present any significant values in our regression analysis when tested individually. Moreover, we presented only the F-value, R^2, Adjusted R^2, and R^2 Change in OLS models with significant results. For instance, for Solar Disinfection, the model presented in Compliance (H1) is only for technology donation individually. Another example we can give is the second column for Flocculation-Disinfection which Compliance and Time x Compliance were significant for Diarrheal risk reduction. We also showed Time, which was not significant, but is within the overall model. This iterative process was performed on all HDWT-based intervention.

For SODIS, the results suggest that time since adoption has no significant effect on compliance, and reduced diarrheal risk. Therefore, technology donation has a significant positive effect on compliance (2.477, $p = .043$).

For chlorination, similar to SODIS, the results suggest no effect of time since adoption on compliance and diarrheal risk reduction. However, they suggest that training to use technology (3.464, *p* = .022), technology donation (3.413, *p* = .020) and compliance (.544, p = .017) exert a significant positive effect in diarrheal risk reduction. On the other hand, unexpectedly, the results also suggest that safe storage donation has a negative effect on compliance (-3.110, *p* = .017) (Table 1).

For the flocculant-disinfectant, the results indicate that the time since the adoption of the technology has a negative effect on the reduction of diarrheal risk (-1.890, *p* = .021), while compliance has a positive effect on diarrheal risk reduction (1.832, *p* = .073). Therefore, unexpectedly, the results also suggest that time (-3.817, *p* = .012), and Technical assistance (-3.374, *p* = .024) have a negative effect on diarrheal risk reduction (Table 1). We also found an interaction effect from time x compliance versus compliance (-1.107, *p* = .050).

For the BSF, the results suggest that time since adoption has no effect on compliance and on diarrheal risk reduction. On the other hand, they show that compliance has a positive effect on diarrheal risk reduction (.883, *p* = .038) (Table 1). The results show that there is an interaction between delivery strategies that lead to an effect on diarrheal risk reduction. We were unable to verify which interactions are significant, as we do not have the absolute values of the primary studies; however, there are strong indications that there is not an individual delivery strategy that leads to a reduction in diarrheal risk, but the interaction between delivery strategies.

Finally, for the CWF, the results indicate that time since technology adoption has a negative effect on compliance (-1.596, *p* = .007); also show that time since adoption versus compliance has a negative effect on diarrheal risk reduction (-.391, *p* = .016). Unexpectedly, the results also suggest that training to use technology has a negative effect on adherence (-.730, *p* = .029) (Table 1).

There was no effect of technology cost (Technology promotional sale) on any of the studied variables (Table 1). This is likely due to the fact that only two studies (one based on chlorine and the other on BSF, marked with * or **, Table S8) required payment for the technology by intervention beneficiaries. In the remaining studies/interventions, technologies were donated. Lack of effect was also observed for Water education and technology promotion, and Diarrhea control diary, on the studied variables.

Our findings show that the effect of HDWT-based interventions to improve drinking water safety, characterized by reduced risk of diarrhea, decreases with increasing time since adoption of HDWT, as shown for flocculant-disinfectant, BSF and CWF (Table 1). This result can be explained, in part, not only by the complexity of behavior change for the adoption of new practices, which normally requires time and continuous activity to stimulate change [202], but also by the barriers identified, whose adverse effects on the HDWT sustained use increases over time. For example, barriers such as difficulty in using the product [57], perception that the treatment process is time consuming [136] and aversion to the taste and/or odor of treated water [130], can hinder the desire to continue using chlorine or flocculant-disinfectant over time, particularly when there is a lack of ongoing activities to encourage consistent adoption [152,223]. Users' inability to correct filter failures [158], filter breakage [157,179], or clogging [52,167] and slow water filtration [180] are some examples of barriers whose effects can lead to a reduction in the protective effect of interventions based on BSF and CWF, especially when users are not routinely assisted by caretakers [109,159]. This serves to emphasize the need for interventions to be durable and to have sustainability as one of the most important pillars.

The results also show that technology donation is a delivery strategy that favors compliance and reduced diarrheal risk by SODIS and chlorination based interventions (Table 1). However, the same strategy was not identified as a differentiating factor for interventions based on flocculant-disinfectant, BSF and CWF. These findings are important for the success and sustainability of interventions when “technology donation” is seen as a means of accelerating and maintaining accessibility and not as a means of free access to technology. On the contrary, the continuous donation of (unnecessary) resources can trigger an undesirable effect, for example, hinder the development of self-sufficiency, in addition to the development of a distorted perception of the main beneficiary of the interventions, which can lead to low adoption and compliance, as previously reported [157].

Table 1. OLS regression estimates for the role of technology delivery strategies used on performance indicators of HDWT-based interventions.

Predictors		**Solar disinfection**		**Chlorination**				**Flocculant-disinfectant**				**Biosand filter**		**Ceramic water filter**		
		Comp.	DRR	Comp.	DRR			Comp.	DRR			Comp.	DRR	Comp.	DRR	
Time		no effect	-	1.186	-.478	-.829	-.593	no effect	-1.89 (p = .02)	3.096	-3.82 (p = .01)	no effect	-.324	-.390	-1.60 (p = .01)	-
Compliance		-	-	-	.54 (p = .02)	-	-	-	-.40 (p = .06)	1.83 (p = .07)	-	-	.88 (p = .04)	-	no effect	-
Time x Compliance		-	-	-	-	-	-	-	-	-1.11 (p = .05)	-	-	-	-	-	-.31 (p = .02)
Technology delivery strategies*	Technology promotional sale	-	-		-		-	-	-	-	-	-	-	-	-	-
	Technical assistance	-	-	-	-	-	-	-	-	-	-3.37 (p = .02)	-	-	-	-	-
	Diarrhea control diary	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	Education and technology promotion	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	Safe storage donation	-	-	-3.11 (p = .02)	-	-	-	-	-	-	-	-	-	-	-	-
	Technology donation	2.48 (p = .04)	-	-	-	3.41 (p = .02)	-	-	-	-	-	-	-	-	-	-
	Training to use technology	-	-	-	-	-	3.46 (p = .02)	-	-	-	-	-	-	-.73 (p = .03)	-	-
F-value		5.80 (p = .04)	-	3.85 (p = .05)	4.51 (p = .05)	4.21 (p = .05)	3.63 (p = .06)	-	9.84 (p = .05)	50.54 (p = .02)	18.8 (p = .02)	-	6.15 (p = .06)	3.61 (p = .08)	12.08 (p = .01)	8.67 (p = .02)
R^2		.420	-	.391	.403	.402	.377	-	.868	.987	.926	-	.755	.474	.573	.491
Adjusted R^2		.348	-	.289	.304	.302	.273	-	.779	.967	.877	-	.632	.343	.526	.434
R^2 Change		.42 (p = .04)	-	.39 (p = .02)	.39 (p = .02)	.38 (p = .02)	.36 (p = .02)	-	.39 (p = .06)	.12 (p = .05)	.45 (p = .02)	-	.57 (p = .04)	.46 (p = .03)	.57 (p = .01)	.49 (p = .02)

Comp. - Compliance. DRR - Diarrheal risk reduction.

However, all sorts of facilitations (e.g. price subsidies, diversification of payment methods) for equitable access to HDWT by populations, especially those with lower economic status, are extremely necessary [221]. The lack of identification of technology donation as a delivery strategy that favors compliance and reduced diarrheal risk is due to the fact that this delivery strategy was used in all the flocculation-disinfection, BSF and CWF-based studies reviewed. In practical application, it has been suggested that the best delivery strategy for HDWT depends on the macroeconomic situation, donor funding, the presence of alternative water treatment options, and the planned timeframe for evaluating results (short- or long-term gains). Thus in certain contexts a greater allocation of grant funds may result in a reduction in long-term adherence [241].

Although training for the use of the technology has been identified as a delivery strategy that favors the reduction of the risk of diarrhea only for SODIS, confirming its importance, the indispensability of adequate training of users extends to all other HDWT. Since good training in the use of technology is critical to a good attitude towards HDWT as well as self-sufficiency, and these two factors together contribute to positive water-related behavior, which in turn favors positive norms. Positive norms reinforce positive water-related behaviors and vice versa, leading to an increasingly sustainable system in terms of HDWT use, both in terms of regularity and number of users [83].

As expected, the results indicate that compliance has a positive effect on reducing diarrheal risk for BSF and SODIS, however, unexpectedly, also suggest that compliance and technical assistance have a negative effect on reducing diarrheal risk for the flocculant-disinfectant based interventions. Likewise, and unexpectedly, the results also suggest that training to use the technology and the donation of container for safe storage of treated water have a negative effect on compliance for CWF and SODIS, respectively (Table 1). The unexpected results need to be interpreted carefully, in practice they mean that studies based on flocculant-disinfectant reporting the use of technical assistance as a delivery strategy and high compliance rates also reported significantly lower rates of diarrheal risk reduction, compared to the alternative. The same explanation is also applicable to the suggested unexpected findings for CWF and SODIS.

Overall, our findings contribute to improving our understanding of the technology delivery strategies used, and how they interact and affect compliance, and the performance of HDWT-based interventions in combating waterborne diseases. However, it must be emphasized that its practical validity still depends on how correctly the strategies are operationalized according to the contextual particularities [73]. Details on how each of the delivery strategies was operationalized in different contexts could not be analyzed in the present study, and this information can be accessed through the original studies.

The following aspects were limitations for the present study: (1) Quantitative data were less frequently reported in studies compared to qualitative data. (2) Most available data on diarrhea prevalence pertain to children. (3) Compliance values are measured in different ways in different studies as well as in different HDWT (availability of treated water, presence of bottles on the roof, presence and/or concentration of residual free chlorine, presence of water in the filter, absence of bacteria in the water). (4 Certain technology delivery strategies exhibited limited variability or lacked variation across specific technologies. (5) A limited number of studies reported certain technology delivery strategies, preventing their inclusion in the analysis.

4. Concluding remarks

A total of 147 studies were included, and from these, 77 barriers and 76 enablers were identified as being interfering with the success or failure of HDWT-based interventions to improve drinking water safety. Each of these barriers and enablers belongs to one of the following domains, Psychosocial, Promotion, Technology, Economic or Environment.

All identified barriers and enablers are critical to early adoption, regularity in use, as well as sustained use of all HDWT, which is why each of these factors should be considered by intervention planners and implementers.

Interventions need to gain the trust of communities, and ensure that high values for psychosocial variables (knowledge, attitudes, social norms) are robustly achieved. They should also ensure the accessibility of technologies, in addition to ensuring that individuals acquire knowledge and skills about the operation, use and maintenance of the HDWT, in a sufficiently robust way to develop users' self-sufficiency.

Intervention implementation activities should be frequent and continuous, and include assistance to users by self-sufficient caretakers, who also carry out routine home visits, and are also available to respond to requests.

Improvements in technologies to overcome important barriers are needed. Goals for technology improvements need to include increased usability, pathogen removal effectiveness, stability, productivity, durability, and robustness of the HDWT.

In general, identifying and/or creating and exploiting the listed enablers will make it possible to overcome most of the reported limitations for all HDWT.

The impacts of HDWT-based interventions tend to decrease with increasing time since the adoption of interventions based on chlorination, flocculation-disinfection, BSF and CWF.

Facilitating access to HDWT (donation) was implicated in favoring compliance, and reducing the risk of diarrhea for interventions based on SODIS and chlorination, respectively. In turn, high compliance values were implicated in contributing to a greater reduction in the risk of diarrhea by interventions based on chlorination, flocculation-disinfection and BSF.

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Conflicts of interest

The authors have no competing interests to declare.

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CAPÍTULO VII

Artigo intitulado “A Challenge in Washing Water with the Sun: 24 hours of SODIS Fails to Inactivate *Acanthamoeba castellanii* Cysts and Internalized *Pseudomonas aeroginosa* Under Strong Real Sun Conditions” Publicado na revista Photochemical & Photobiological Sciences . https://doi.org/10.1007/s43630-023-00440-2

A challenge in washing water with the sun: 24 hours of SODIS fails to inactivate *Acanthamoeba castellanii* cysts and internalized *Pseudomonas aeruginosa* under strong real sun conditions

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ABSTRACT

Despite access to drinking water being a basic human right, the availability of safe drinking water remains a privilege that many do not have and as a result, many lives are lost each year due to waterborne diseases associated with the consumption of biologically unsafe water. To face this situation, different low-cost household drinking water treatment technologies (HDWT) have been developed, and among them is the solar disinfection (SODIS). Despite the effectiveness of SODIS and the epidemiological gains being consistently documented in the literature, there is a lack of evidence of the effectiveness of the batch-SODIS process against protozoan cysts as well as their internalized bacteria under real sun conditions. This work evaluated the effectiveness of the batch-SODIS process on the viability of *Acanthamoeba castellanii* cysts, and internalized *Pseudomonas aeruginosa*. Dechlorinated tap water contaminated with 5.6 x 10^3 cysts/L, contained in PET (polyethylene terephthalate) bottles, was exposed for 8 hours a day to strong sunlight (531 to 1083 Wm^{-2} of maximum insolation) for 3 consecutive days. The maximum water temperature inside the reactors ranged from 37 to 50°C. Cyst viability was assessed by inducing excystment on non-nutrient agar, or in water with heat-inactivated *Escherichia coli*. After sun exposure for 0, 8, 16 and 24 h, the cysts remained viable and without any perceptible impairment in their ability to excyst. 3 and 5.5 log CFU/ml of *P. aeruginosa* were detected in water containing untreated and treated cysts, respectively, after 3 days of incubation at 30°C. The batch-SODIS process is unable to inactivate *A. castellanii* cysts as well as its internalized bacteria. Although the use of batch SODIS by communities should continue to be encouraged, SODIS-disinfected water should be consumed within three days.

Keywords: Solar disinfection, Protozoan cyst resistance, Endosymbionts, Point-of-use water treatment, Internalized bacteria, Endosymbiont.

INTRODUCTION

Despite considerable increases in rates of access to improved sources of drinking water over the past century, inequalities in access to safe water remain high across the world; consequently, 829,000 human lives are lost annually due to waterborne diseases (Prüss-Ustün et al. 2019; Bain et al. 2021; UN 2022). A large proportion of these deaths are reported from low-income developing countries (mainly from Africa (53%) and Southeast Asia (38%)), which proportionally concentrate the majority of people who consume water collected from unimproved sources (Bain et al. 2014; UN 2022).

Achieving universal and equitable access to clean water for all by 2030 is one of the objectives of the sustainable development goals - SDG (UN 2022). Achieving this goal is challenged by the high financial investment (US$37.6 billion) that needs to be made annually (for 15 years) to extend clean water services to populations without access to improved sources of drinking water in the world (Guy and Mili 2016). To face the existing financial challenge, different low-cost household drinking water treatment technologies (HDWT) were developed (Nielsen et al. 2022; Freitas et al. 2022; Chaúque and Rott 2021; Akowanou and Aina 2021; Souter et al. 2003; Baker and Taras 1981). Solar disinfection (SODIS) is listed among the recognized leading low-cost HDWTs (WHO 2019), and its real-life use by interventions aimed at improving the safety of drinking water has been widely associated with a reduction in the risk of diarrheal diseases (20 -75%) in various contexts (Rai et al. 2010; Soboksa et al. 2020; McMahon, 2022). These epidemiological gains have been attributed to the induction of protective immunological changes in SODIS users (Ssemakalu et al. 2014; Chaúque et al. 2022), as well as to the improvement of the microbiological quality of drinking water due to the practice of SODIS (McGuigan et al. 2012; Chaúque and Rott 2021). In general, the improvement in the microbiological quality of water results from the biocidal effect of ultraviolet (UV) radiation combined with solar heat on the microorganisms present in the water (Hong et al. 2022; Castro-Alférez et al. 2018). The biocidal capacity of SODIS has been widely demonstrated with success against medically important representatives of almost all microbial taxa, including viruses (Amatobi and Agunwamba 2022); Chaúque et al. 2022a), bacteria (García-Gil et al. 2022), fungi (Xia et al. 2022a), and protozoa (McGuigan et al. 2006). There is little evidence of the effectiveness of SODIS against environmental resistance structures of microorganisms (e.g. cysts), especially, the literature lacks studies on the effect of the batch-SODIS process under real sunny conditions on the viability of *Acanthamoeba* spp. cysts.

Acanthamoeba is a genus formed by protozoans known to be ubiquitous, which have been isolated from almost all environmental compartments (Bellini et al. 2022; Visvesvara et al. 2007), and are highly prevalent in water (Chaúque et al. 2022b). *Acanthamoeba* spp. cysts are resistant to a wide variety of biocidal factors (such as UV and gamma radiation, moist heat, high concentrations of chlorine and NaCl) (Aksozek et al. 2002; Cervero-Aragó et al. 2013; Chaúque and Rott 2021a) and inhospitable conditions (drying and prolonged freezing) (Sriram et al. 2008).

Despite the medical importance of *Acanthamoeba* spp. be related to infections of other organs (brain, urinary tract, eyes, skin) and not of the digestive tract (Sarink et al. 2022; Milanez et al. 2022; Saberi et al. 2021; Santos et al. 2021; Santos et. al. 2018), its importance for the safety of drinking water comes from the fact that these microorganisms are involved in the expression of pseudo-resistance by enteric pathogens to different water disinfectants. Pseudo-resistance occurs through regrowth of microorganisms in disinfected water (without external recontamination) and has been demonstrated for different water treatment processes including chlorination (Thomas et al. 2004) and UV disinfection (Boratto et al. 2014; Cervero-Aragó et al. 2014). This phenomenon occurs because trophozoites (which are the vegetative form of the protozoan) feed on particulate matter and microorganisms, including pathogenic microorganisms (Thomas et al. 2004; Thomas et al. 2010). Many of these microorganisms escape the digestive pathways of the cell and survive inside the protozoan, being able to multiply and recombine their genetic material (Thomas et al. 2010), which is why they are called amoeba-resistant microorganisms (ARM) and/or amoebic endosymbionts. 18.9% (102/539) of the bacteria described as pathogenic (for humans and/or animals) were described as ARM, as is the case for *Pseudomonas aeruginosa* (Thomas et al. 2010). The ARM present inside *Acanthamoeba* spp. remain protected from disinfectants that are ineffective against this protozoan, being constantly released inside vesicles to the extra amoebic environment recolonizing previously treated water (Thomas et al. 2004; Dey et al. 2021).

The study of the effectiveness of SODIS against cysts of *Acanthamoeba* spp. and their internalized microorganisms is therefore necessary. Although there are some studies dealing with the inactivation of *Acanthamoeba* sp. by SODIS, these are based on simulated SODIS conditions (Lonnen et al. 2005; Heaselgrave et al. 2006; Heaselgrave and Kilvington 2010, 2011), or using SODIS systems (Chaúque et al. 2021a). The present study is the first to evaluate the effect of the batch-SODIS process on the viability of *Acanthamoeba castellanii* cysts and internalized *P. aeruginosa* under real sun conditions.

MATERIAL AND METHODS

Preparation of *A. castellanii* cyst stock without and with internalized *P. aeruginosa*

The cysts were produced from trophozoites of *Acanthamoeba castellanii*, strain Neff, ATCC 30010. Trophozoites were cultured axenically in PYG medium ((2% peptone proteose, 0.2% yeast extract and 1.8% glucose), intcubated at 30°C for 7 days. Then, the PYG medium was replaced by Neff's encysting solution (0.1 M KCl, 0.02 M Trisamine, 8 mM MgSO4, 0.4 mM CaCl2, 1 mM NaHCO3) and incubated at 30°C for more than 7 days. The PYG medium and the Neff’s *encystmen**t*** solution were supplemented with antibiotic (10,000 UI/mL of penicillin and 10,000 µg/mL of streptomycin).

Cysts with internalized *P. aeruginosa* were obtained by inducing encystment of trophozoites containing internalized bacteria. The production of trophozoites containing internalized bacteria was performed according to the procedures detailed by Dietersdorfer et al. (2016) to internalize *Legionella pneumophila*. Briefly, *Pseudomonas aeruginosa* PAO1 with a transposon-inserted green fluorescent protein (PAO1-Tn7-GFP) was grown in Brain Heart Infusion (BHI) broth at 37 °C for 18 h. Bacteria were washed twice by centrifugation (1000 x *g* for 5 min) and resuspended in phosphate buffer solution (PBS). Bacteria (8 x 10^7 cfu/mL) were added to 15 ml Falcon® conical tubes containing *A. castellanii* trophozoites (4 x 10^5 cell/mL) in a 200:1 ratio of bacteria and trophozoites, respectively. The solution was gently vortexed, centrifuged (500 × *g* for 10 min), transferred to a 12-well plate, and then incubated at 30°C for 2 hours. After this time, the solution was gently replaced by fresh PBS, supplemented with gentamicin (50 µg/mL) and then incubated at 30°C for 24 h. The solution was replaced by PYG medium supplemented with gentamicin (50 µg/mL) and incubated at 30ºC for 48 h. The trophozoites were then transferred and multiplied in a culture bottle and kept in PYG supplemented with gentamicin and cultured for up to two months (washing and replacing the medium every four days). Trophozoites containing internalized *P. aeruginosa* were collected periodically for cyst production (according to the procedures described above).

To eliminate trophozoites, as well as bacteria in the extracystic environment, the cyst stock was subjected to two successive stages of mechanical lysis, i.e. passage through a 26-gauge needle (7 times) followed by centrifugation (10,000 x g for 10 min) (Dey et al. 2019), and after washing twice, the cysts were suspended in the Neff's *encystment* solution supplemented with 50 µg/mL of gentamicin and incubated at 30ºC for 72 hours. The absence of bacteria in the extracystic environment was certified by culturing aliquots of the cyst stock on MacConkey agar and incubating at 37ºC for up to 48h.

The presence of bacteria inside the stored cysts was monitored and confirmed every three weeks, according to previously described methodologies (Heaselgrave et al. 2006; Dietersdorfer et al. 2016). Briefly, an aliquot of cysts was washed twice (2,500 x g for 5 min) and transferred to a well (of 24-well plate) containing PBS and suspended heat-inactivated *E. coli*. The plate was incubated at 30ºC for 5 days, then gently washed (keeping the trophozoites adhered), adding PYG supplemented with gentamicin, and incubated for another 3 days. After that, the trophozoites were collected, washed (1,500 x g for 5 min), submitted to mechanical lysis (passage through a 26 gauge needle) and the resulting solution cultured in MacConkey agar and incubated at 37ºC for up to 48h. Recovery of *P. aeruginosa* from lysed trophozoites was achieved throughout the cyst storage period (up to two months).

Cysts suspended in the encysting solution were kept at 4°C, and their viability was confirmed by exclusion staining test with 0.4% trypan blue before use in tests.

Conducting SODIS tests

Cysts without (1.1 x10^6 cysts/mL) and with *P. aeruginosa* (1.2 x10^6 cysts/mL) were mixed and then added to dechlorinated tap water at a density of 5.6 x10^3 cysts/L. Quantification of residual free chlorine in water was performed by the N,N-diethyl-p-phenylenediamine (DPD) method (APHA 2005), and complete inactivation of chlorine in water was achieved by the addition of sodium thiosulphate (4 mg/L).

A conventional batch-SODIS was performed using polyethylene terephthalate (PET) bottles as a reactor. Contaminated water was poured into PET bottles and shaken vigorously before filling them completely. The bottles contain inserted thermal probe, were placed on a white metallic surface previously positioned in a sunny place. The bottles were exposed for 8 hours (9:00 am to 5:00 pm) per day to the strong summer sun (sunrise 05:40 am - sunset 07:20 pm) for three consecutive days (22, 23, 24 and 25/12/2022).

The experiments were performed in triplicate with three repetitions, two repetitions (6 bottles) were exposed during the first three days and another repetition (3 bottles) was exposed during the last three days. Samples (100 mL) were collected before the first exposure to the sun (control) and at the end of each session of the experiment, on days 1, 2 and 3, corresponding to 8, 16 and 24 hours of sun exposure. After sample collection, a corresponding volume (100 mL) of autoclaved tap water was added to replenish the PET bottles. The samples were preserved at 4ºC until the microorganism viability analyzes were carried out.

The radiological data (Global radiation and Environmental Temperature (Figure 1 A), and UV radiation (Figure 1 B) were measured by automatic stations A801 and 83971, all located 6.5 km from the place where the PET bottles were exposed (latitude -30.05, longitude -51.16, and latitude -29.99, longitude -51.17, Porto Alegre, Brazil, respectively). Meteorological stations belonging to the National Institute of Meteorology (INMET) (http://www.inmet.gov.br), and the National Institute for Space Research (INPE) (http://satelite.cptec.inpe.br) respectively. The temperature of the water inside the PET bottles was recorded every hour and the corresponding data are shown in Figure 2.

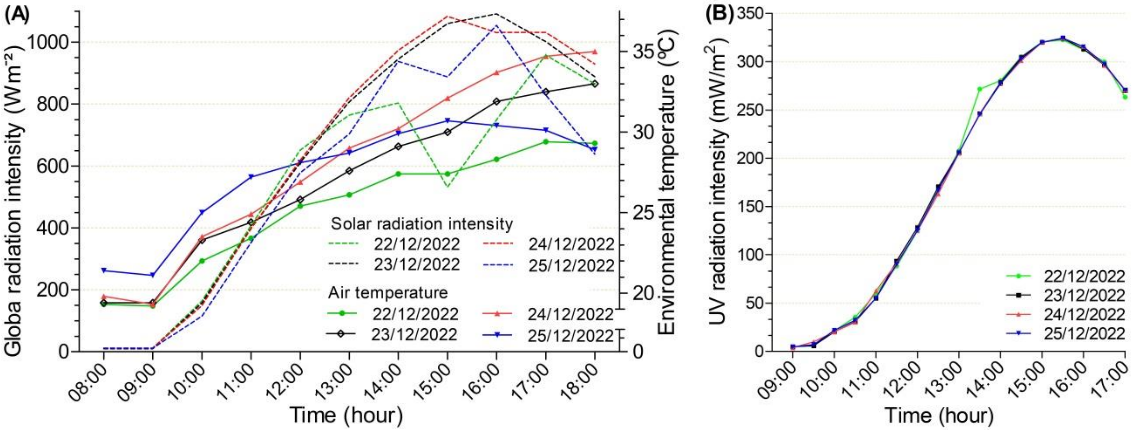

Figure 1. Radiological conditions and ambient temperature on the days of the experiment.

Viability analysis of microorganisms

They were started the day after the last sun exposure (day 4). 45 mL of sample (previously homogenized) was centrifuged (2,500 x *g* for 5 min) and the pellet was resuspended in 100 µL. The viability analysis of the cysts by plaque excystment was performed as previously described (Chaúque and Rott, 2021a). Briefly, 25 µL of the sediment was deposited in duplicate on the surface of non-nutrient agar (NNA) 1.5 % containing a previously spread layer of heat-inactivated *Escherichia coli*. After drying the spots, the inverted plates were incubated at 30°C for 9 days, being checked after 3, 6 and 9 days of incubation, counting the trophozoites visualized in four fields (10X) randomly selected around the spot.

The remaining 50 µL of the pellet was transferred to a well of the 24-well plate containing 1 mL of autoclaved tap water and 25 µL of heat-inactivated *E. coli* (6 log/mL). The plate was incubated at 30°C and monitored for trophozoite counts 3 and 6 days later. The trophozoite count was performed in four fields (10X) randomly selected. 100 µL of water was taken from each of the wells on the fourth day of incubation, then subjected to serial dilution and seeded in Cetrimide agar using the drop plate technique (Garre et al. 2019) to quantify *P. aeruginosa*. The plates were incubated at 37ºC for 48 hours, and the greenish colonies were counted.

Data analysis

The significance (P value < 0.05) of differences between data was determined using the two-tailed paired t test, (after verifying the normality of the data by the Shapiro-Wilk test at 5%) using the BioEstat 5.0 software. The GraphPad prism 8.02 program was used to plot graphs.

RESULTS

From the initial 23ºC, the water temperature rose and reached peaks of 37 – 50ºC; higher temperatures (2 to 6°C higher) were recorded in green PET bottles compared to colorless bottles (Figure 2).

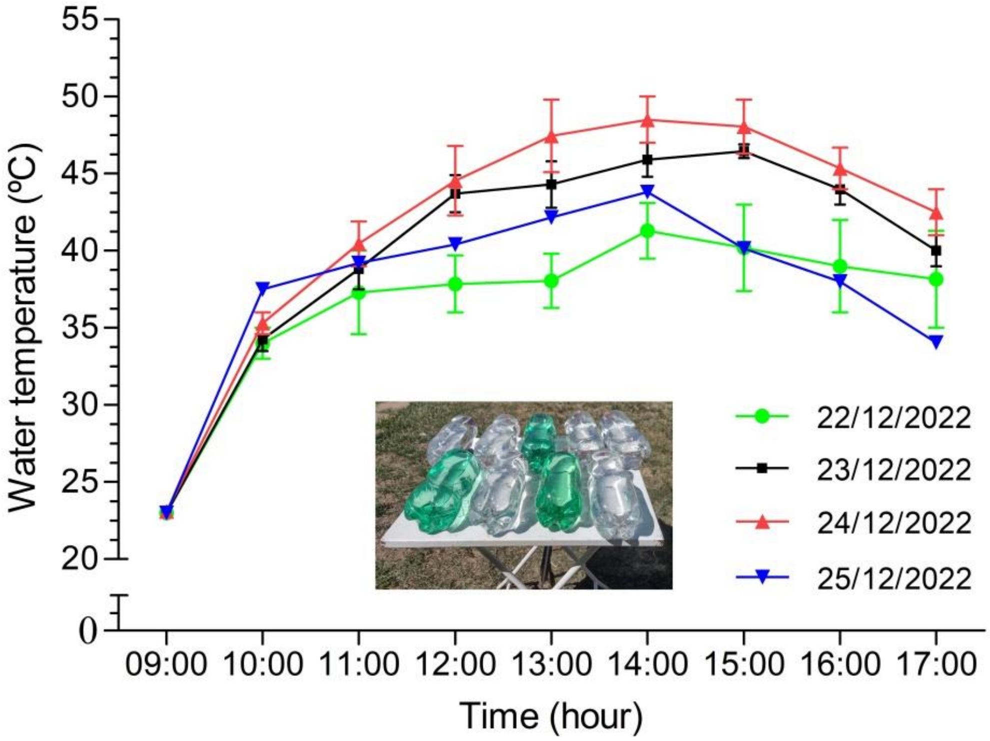

Figure 2: Water temperature variation inside the PET bottles during the experiment.

The cysts remained viable and excysted after being submitted to all times of sun exposure (8 – 24 h) (Figure 3). Although the data suggest that excystment rate is higher in NNA (Figure 3 A) than in water (Figure 3 B), overall (considering the joint variability of the data) it does not differ significantly between the two methods (P < 0 .05).

The number of trophozoites recovered from untreated cysts was not higher than that obtained from treated cysts, and in some cases was similar or significantly lower ($P < 0.05$) in the NNA excystment method (Figure 3A). The number of trophozoites obtained from untreated cysts did not differ significantly from the number obtained from treated cysts ($P < 0.05$) in the excystment in water method (Figure 3B).

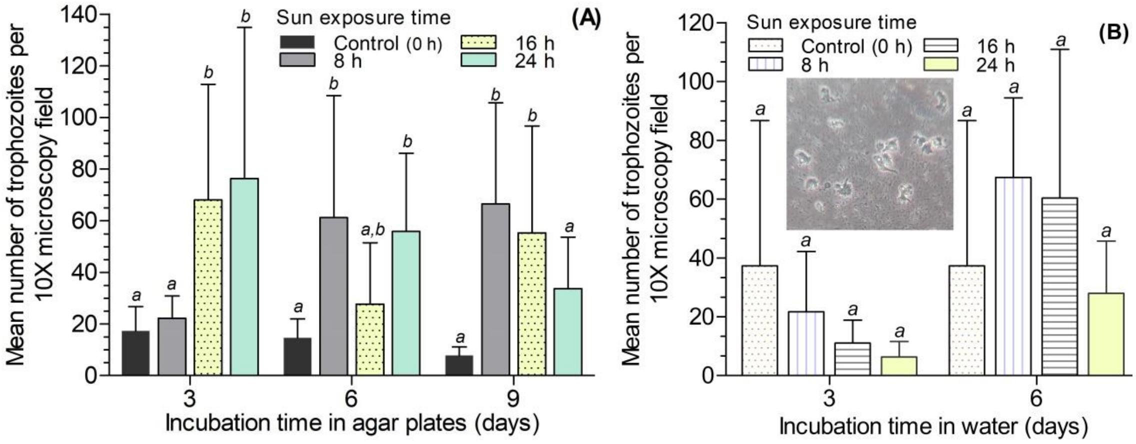

Figure 3. Number of trophozoites obtained from cysts subjected to different times of sun exposure (0, 8, 16 and 24 h), by inducing excystment in non-nutritive agar (A) or in water (B). Columns marked with different letters per subgroup mean a statistically significant difference ($P < 0.05$).

P. aeruginosa was detected in water containing cysts subjected to all times of sun exposure (0, 8, 16 and 24 h) (Figure 4). The number of colony forming units detected in water containing treated cysts was statistically similar or higher than that detected in water containing untreated cysts ($P < 0.05$).

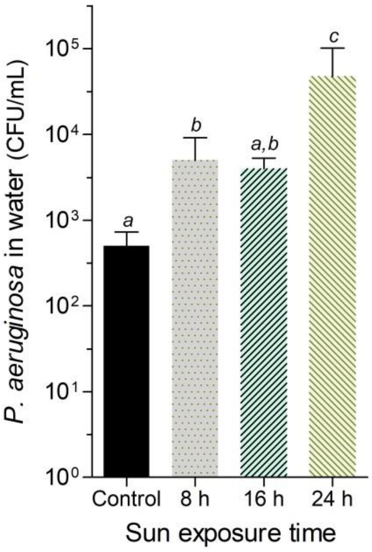

Figure 4. Amount of *P*. *aeruginosa* detected in water containing cysts subjected to different times of sun exposure. Columns marked with different letters mean a statistically significant difference ($P < 0.05$).

DISCUSSION

Although several research groups have sought to answer the question about the concern about the effectiveness of the batch-SODIS process on protozoan cysts (Lonnen et al. 2005; Heaselgrave et al. 2006; Heaselgrave and Kilvington, 2010, 2011), the question remains unanswered for SODIS in real sunny conditions. Likewise, the question about the effectiveness of batch-SODIS against microorganisms internalized by encysted protozoa still needs to be answered. The present work aimed to answer these questions.

Our results indicate that *A. castellanii* cysts are resistant to the batch-SODIS process under natural sunny conditions, including three days' exposure to strong sunlight. These findings confirm the conclusions of laboratory studies based on simulated solar radiation, stating that SODIS is ineffective against cysts of *Acanthamoeba* spp. (e.g. Lonnen et al. 2005; Heaselgrave and Kilvington, 2010).

The literature indicates that the inactivation of *Acanthamoeba* spp. (> 3 log) in disinfection processes comparable to batch SODIS, occurs when the cysts are exposed to the synergistic effect of UV radiation and ≥ 50 and 55ºC, for 6 and 4 h, respectively (Heaselgrave et al. 2006), or UV and ≥ 60ºC for ≤ 10 minutes (Chaúque et al. 2021a). In the present study, although a temperature of 50ºC was reached, it was maintained for ~3 h (Figure 2), explaining the impossibility of achieving cyst inactivation. Similar or lower maximum temperatures, ranging between 50 and 27 ºC, have been reported in other studies (Amirsoleimani and Brion, 2021; Aquinaga and Medeiros, 2022).

Our results also show that although the batch SODIS is widely documented to be effective against bacteria (Karim et al. 2021; Nwankwo et al. 2019; McGuigan et al. 2012), it is ineffective when these bacteria are harbored within cysts of *Acanthamoeba* spp. (Figure 4). These results are in line with the findings of other studies that reported the persistence of viruses and bacteria internalized by *Acanthamoeba* spp. in water disinfected by UV, and heat (45 - 65ºC) (Boratto et al. 2014 Cervero-Aragó et al. 2014).

The pseudo-resistance displayed by bacteria and/or viruses (well known to be susceptible) against water disinfection processes in the presence of amoebae is attributed to rapid internalization (Hsueh and Gibson 2015; Verani et al. 2016; Rayamajhee et al. 2021) and the protection of bacteria by amoebae resistant to the disinfectants used. The cystic form of amoebae is much more resistant to different biocides (Aksozek et al. 2002), and this is due to the fact that they are covered by a cellulosic double wall (Garajová et al. 2019) that is essentially opaque to radiation, impermeable to chemical biocides and resistant to mechanical shocks. The persistence of bacteria harbored in amoebic spores of *Dictyostelium discoideum*, including inactive ones, against water disinfectants is also documented in the literature (He et al. 2021).

Practical implications

Although the genus *Acanthamoeba* (like other free-living amoebae) includes pathogens and/or opportunists (Vivesvara et al. 2017; Rayamajhee et al. 2021) they are not waterborne gastrointestinal pathogens. Despite this, the inability of SODIS to inactivate *Acanthamoeba* spp., combined with the ubiquity of amoebae in water from different sources (Sente et al. 2016; Aykur and Dagci, 2021), and the co-occurrence of enteropathogenic bacteria and/or viruses in these waters (Yousuf et al. 2017; Lorenzo-Morales et al. 2017; Valciņa et al. 2019), raises concerns about this technique of providing drinking water. It should be noted that bacterial and/or viral enteropathogens are practically omnipresent in drinking water sources used by needy communities (Horn et al. 2016; Upfold et al. 2021; Chaúque et al. 2021b) mainly because in these contexts they persist sanitation challenges (Ngasala et al. 2019; Chaúque et al. 2021b). The concern that arises on this subject can be summarized in the possibility of recolonization (often called regrowth by the authors) of SODIS-disinfected water by enteropathogenic microorganisms. These microorganisms are constantly released into the extra-trophozoite environment in vesicles filled with infectious units (Dey et al. 2019, 2021). In the case of cysts, the presence of bacteria in the water induces rapid excystment (2 to 3 days) of *Acanthamoeba* and multiplication of trophozoites (Figure 3), which may later result in the beginning of the release of internalized microorganisms and the consequent recolonization of the water. Thus, safe SODIS-disinfected water may become unsafe for human consumption within a few days of storage. It is important to mention that the pathogens released by the amoeba can be more pathogenic than they were before its internalization, as, for example, demonstrated for *Campylobacter jejuni* (Nasher and Wren, 2022).

RECOMMENDATIONS

The use of batch-SODIS process needs to continue to be encouraged, as it is a low-cost method of providing potable water, and its use on a community scale has resulted in epidemiological gains (Wolf et al. 2022; Soboksa et al. 2020). However, consumption of SODIS-disinfected water should be avoided after three days of storage.

It is necessary to develop new (low-cost) reactors for SODIS that allow the efficient use of heat and solar UV radiation synergistically. Reactors are needed with a wall with high transmittance to UV radiation and, at the same time, with a good ability to quickly absorb and retain heat from the sun. The integration of low-cost mechanisms to monitor the UV radiation dose is also desirable. The devices developed and tested by Farhadi et al. (2022) and by Sales-Lérida et al. (2023) are examples of possibilities to be considered.

The development of functionalized reactors or reservoirs with biocidal properties to store SODIS disinfected water (e.g. copper-based materials (Sharan et al. 2011)) to prevent recolonization of water by pathogens (in case of prolonged water storage) are highly desirable.

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ETHICAL APPROVAL

Not applicable

CONSENT TO PARTICIPATE

Not applicable

CONSENT TO PUBLISH

Not applicable

AUTHORS CONTRIBUTIONS

BJMC, GC, ADB, and MBR contributed to the study conception and design. Material preparation, data collection analysis, and writing the first draft of the manuscript were performed by B.J.M.C. GC, ADB, and MBR reviewed the manuscript writing. All authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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COMPETING INTERESTS

The authors have no relevant financial or non-financial interests to disclose

AVAILABILITY OF DATA AND MATERIALS

Not applicable

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CAPÍTULO IX

Manuscrito intitulado “Preliminary insights on the development of a continuous-flow solar system for the photocatalytic degradation of contaminants of emerging concern in water” submetido a revista Environmental Science and Pollution Research, http://dx.doi.org/10.1007/s11356-024-32879-w.

Preliminary insights on the development of a continuous-flow solar system for the photocatalytic degradation of contaminants of emerging concern in water

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ABSTRACT

The ubiquity and impact of pharmaceuticals and pesticides, as well as their residues in environmental compartments, particularly in water, have raised human and environmental health concerns. This emphasizes the need of developing sustainable methods for their removal. Solar-driven photocatalytic degradation has emerged as a promising approach for the chemical decontamination of water, sparking intensive scientific research in this field. Advancements in photocatalytic materials have driven the need for solar reactors that efficiently integrate photocatalysts for real-world water treatment. This study reports preliminary results from the development and evaluation of a solar system for TiO_2-based photocatalytic degradation of intermittently flowing water contaminated with doxycycline (DXC), sulfamethoxazole (SMX), dexamethasone (DXM), and carbendazim (CBZ). All substances were present at a concentration of 1.0 mg/L, except for DXM (0.8 mg/L). The system consisted of a Fresnel-type solar concentrator that focused on the opening and focal point of a parabolic trough concentrator, within which tubular quartz glass reactors were fixed. The reactors contained concentric springs coated with TiO_2 arranged one inside the other. The water underwent sequential batch processing with retention times of 15, 30, 60, 90, and 120 minutes. After 15 minutes, the degradation rates were as follows: DXC - 87%, SMX - 35.5%, DXM - 32%, and CBZ - 31.8%. The system demonstrated the capability to process 101 liters of water daily, indicating its potential for real-world chemical water decontamination applications. Further enhancements that enable continuous-flow operation and integrate highly effective adsorbents and photocatalytic materials can significantly enhance system performance.

Keywords: TiO_2, high water productivity, doxycycline, sulfamethoxazole, dexamethasone, carbendazim, solar reactor.

Introduction

The widespread presence of xenobiotics, including pharmaceuticals, agrochemicals, or their residues in various environmental matrices, has emerged as a significant concern in recent years (Githaiga et al. 2023). These compounds, derived from human, agricultural, and veterinary activities, are entering water bodies, soils, polar ice caps, and even the atmosphere, posing risks and potential consequences for both ecosystems and human health (Patel et al. 2019; Arsand et al. 2023). The pathways by which pharmaceuticals and pesticides disperse within the environment are complex, involving elements like incorrect application and disposal, insufficient wastewater treatment, and runoff from agricultural activities (Patel et al. 2019; Zhang et al. 2022; Ding et al. 2023; Marutescu et al. 2023). This escalating issue has sparked concerns due to the potential of these contaminants to bioaccumulate and cause long-term effects on aquatic organisms, terrestrial ecosystems, and the entirety of the food chain (Liu et al. 2021; Rahman and Hollis 2023). Moreover, the occurrence of pharmaceuticals and pesticides within various environmental compartments exacerbates the escalating global issue of antimicrobial resistance. This, in turn, poses an additional challenge in the fight against infections and the control of pest populations (Bengtsson-Palme et al. 2018; Wang et al. 2023).

Doxycycline (DXC) is an antimicrobial from the tetracycline class, used in human and veterinary medicine, detected in surface waters (27 – 82.2 ng/L) and sewage (43 – 444 ng/L) (Singer et al. 2014; Deng et al. 2016). Its environmental stability, including slow photodegradability by UV radiation, was recognized, and 6 hours of low-concentration drug (0.06 mg/L) exposure to UV-C (254 nm, 3216 $\mu W/cm^2$) caused only 5% degradation (Berdini et al. 2022). Furthermore, tetracycline (50 mg/L, 400 mL) exposed to UV-A radiation (352 nm, 1.45 mW/cm^2) completely degraded within 14 days (Yun et al. 2018). The presence of DXC (1 mg/L) in water has been linked to a decrease in fecundity and significant alterations in the microbiome of *Daphnia magna* (Carrillo et al. 2023).

Sulfamethoxazole (SMX) is among the most frequently detected ecotoxic antimicrobials in various water sources worldwide. Its presence has been documented in a wide range of concentrations in effluents (10 – 1,000 ng/L) and surface waters (1.5 – 10,000 ng/L). Its strong toxicity has been documented in marine life at low concentrations (C_{50}), including algae (0.2 – 1.2 mg/L), cyanobacteria (~0.7 mg/L) and plants (0.08 – 0.2 mg/L) (Kovalakova et al. 2020). The high toxicity of SMX leading to mortality, malformation, brain edema, and physiological effects, has also been reported in zebrafish at concentrations of 1 µg/L (Lu et al. 2022; Xu et al. 2022).

Dexamethasone (DXM) is a widely used synthetic glucocorticoid known for its potent ecotoxic effect. Its presence in waters from various sources has been extensively documented worldwide (Musee et al. 2021), with environmental concentrations ranging from 0.02 to 1,720 ng/L (Shen et al. 2021; Ammann et al. 2015). At concentrations as low as parts per billion, DXM has been shown to have harmful ecological impacts on aquatic organisms, including crustaceans and fish (Musee et al. 2021).

Carbendazim (CBZ) is a synthetic fungicide belonging to the benzimidazole class, widely used worldwide. Although it is effective, it also has a broad toxicological impact on microorganisms, animals and humans, with the potential to cause embryonic, developmental, endocrine and hematological toxicities (Zhou et al. 2023). While most studies (Singer et al. 2010; Montagner et al. 2014; Launay et al. 2016; Ccanccapa et al. 2016; Merel et al. 2018) have reported concentrations of its occurrence in surface waters ranging from 10 ng/L to 50 ng/L, higher values were also documented, such as 600 ng/L (Masiá et al. 2015). The presence of CBZ in surface water bodies has been positively correlated with the presence of pharmaceuticals in water, primarily attributed to discharges of domestic wastewater, including treated effluents (Merel et al. 2018).

Dealing with this complex issue requires a concentrated effort to develop effective mitigation strategies. A promising approach involves removing or degrading these products from water bodies. A solar photocatalysis has garnered attention among the potential strategies due to its environmentally friendly and cost-effective attributes (Lupu et al. 2023). This method harnesses solar energy to degrade or inactivate chemical and microbial pollutants in water, offering a promising avenue for pollution control (Hadei et al. 2021; Chaúque and Rott, 2021; Silerio-Vázquez et al. 2022; Ge et al. 2023). Photocatalysis utilizes semiconductor-based materials to catalyze chemical reactions upon exposure to light, resulting in the complete degradation or conversion of contaminants into less or more harmful substances that can be readily removed through subsequent decontamination steps (Hadei et al. 2021; Boulkhessaim et al. 2022).

Nonetheless, despite its considerable potential, the real-world application of solar photocatalysis for degrading pharmaceutical and pesticide contaminants in water faces certain limitations, mainly related to scalability (Rahman et al. 2023; Mishra and Sundaram 2023; Gualda-Alonso et al. 2023). The lack of robust systems capable of efficiently processing large volumes of water hinders its wide application, and requires further research and technological advances to make this approach viable and impactful on a broader scale. Furthermore, the long exposure time required to achieve relevant levels of contaminant removal is an important challenge in large-scale processes (Gualda-Alonso et al. 2022; Gopalakrishnan et al. 2023).

The present study reports the development and testing of a continuous-flow solar system for photocatalytic degradation of DXC, SMX, DXM and CBZ in water, using TiO_2 as photocatalyst. We found that the system has the potential to be applied in real-world wastewater decontamination situations, as substantial simultaneous removal of these products was achieved in 15 minutes. The challenges encountered and the mechanisms to increase the effectiveness of the developed system are explored and discussed.

Materials and Methods

Chemicals

Carbendazim (CBZ, 97%) was obtained from Sigma-Aldrich. Dexamethasone (DXM) was procured from TEUTO Laboratories (Anápolis, GO, Brazil). Sulfamethoxazole (SMX) and Doxycycline (DXC) were custom-produced by Vida Animal Laboratories (Porto Alegre, Brazil). Titanium dioxide (TiO_2, 99.9%) was purchased from DINAMICA (Brazil).

System construction

The system employed in this study was previously designed and constructed as described in prior publications (Chaúque et al. 2023; Chaúque et al. 2021). However, for the present investigation, only the component responsible for collecting and utilizing UV solar radiation was utilized (Fig. 1). Briefly, the system comprises a Fresnel solar concentrator coupling a parabolic trough concentrator (PTC) at its focus. The PTC contains three tubular quartz reactors (each measuring 34 x 30 x 1500 mm, with UV A and B transmittance of

91.6%), fixed at the opening and focal line of the PTC. The Fresnel concentrator (collection area 1.5 x 8.0 m) consisted of a set of flat plates (1.5 x 0.22 m) lined with aluminum adhesive films (average UV reflectance, 74.7%) fixed sequentially on movable stainless steel supports. The PTC was made of aluminum and its reflective face was also coated with aluminum adhesive film. The system can track solar radiation in two axes, thanks to its configuration that includes a set of rotating wheels, axles, a metallic arm, and a lever. These components enable the adjustment of the entire structure and/or flat collectors, ensuring the system remains focused.

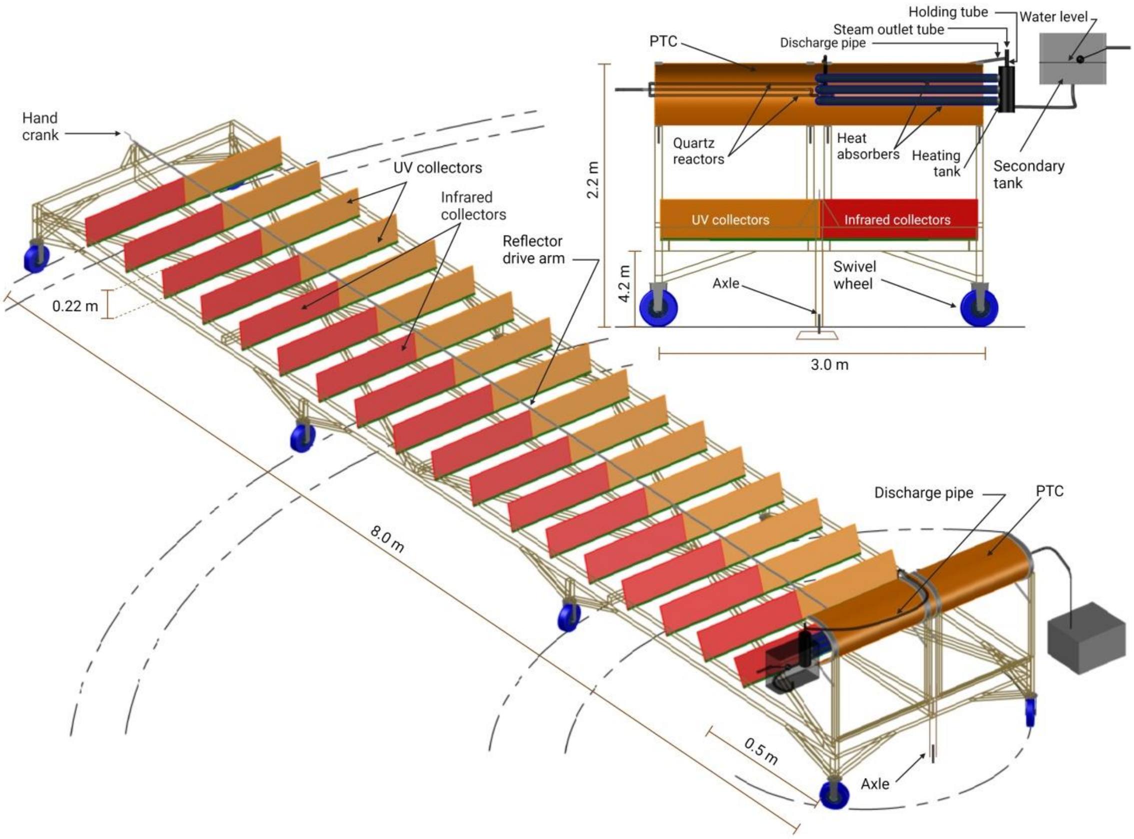

Fig. 1: General schematic representation of the system's constituents, of which only the UV part was explored in this work. With permission, licence: 5638310689519 (Chaúque et al. 2023).

Inside the quartz tubular reactors, supports coated with photocatalytic material (TiO_2) were placed. These supports consist of two concentric springs with external diameters of 28 mm and 19 mm, respectively, made from 1.5 mm thick copper wire (Fig. 2). To attach the TiO_2, the support was immersed in liquid PVC glue, vigorously shaken to remove excess glue, and then coated with TiO_2 powder. The assembly was left to dry for 24 hours at room temperature. Following this, the TiO_2-coated supports were rinsed twice with water jets to eliminate any inadequately adhered TiO_2 and subsequently left to dry again at room temperature for 24 hours before being placed into the quartz tubes.

Support portions measuring 21 cm in length were utilized for ease of TiO_2 fixation. On average, each support portion contained 15 g of TiO_2, resulting in a total of approximately 90 g of TiO_2 in each of the three quartz reactors. The amount of TiO_2 was determined by subtracting the weight of the support coated with TiO_2 from the weight of the support covered only with dry glue. These measurements were conducted four times using randomly selected supports.

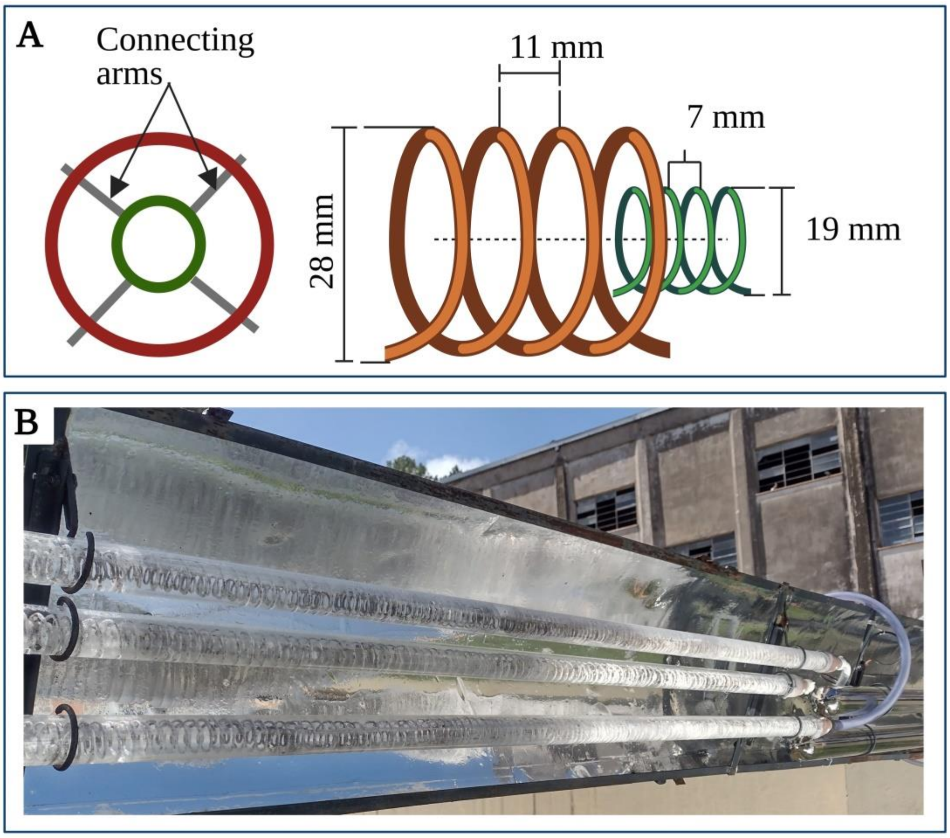

Fig. 2. Schematic representation of the concentric springs serving as TiO_2 support (A), photo of the quartz tubular reactors containing TiO_2-coated supports inside, fixed to the opening of the parabolic trough concentrator (B).

The quartz tubular reactors, containing TiO_2-loaded supports, were fixed horizontally in the PTC opening. Specifically, the intermediate tube was positioned at the focal line of the PTC. These reactors are interconnected using plastic tubes. The lower reactor is connected to the raw water tank through a crystal PVC tube, facilitating the flow of water to the intermediate reactor and subsequently to the upper reactor. A check valve was also installed on the discharge piping connected to the upper reactor nozzle.

System operation and photocatalytic experiments

Once the system was focused, raw water containing pharmaceuticals and pesticides was allowed to flow into the reactors until they were completely filled, at which point the check valve was closed, for 15, 30, 60, 90, and 120 minutes.

The experiments were conducted during three days, specifically on April 10th, 11th, and 12th, 2023, which corresponds to the autumn season in Rio Grande do Sul, Brazil. Solarimetry was performed at two meteorological stations located 6.5 km from the experiment site, namely, station A801 (latitude -30.053, longitude -51.174, altitude 41.18 m) of the National Institute of Meteorology (INMET) (http://www.inmet.gov.br/portal/), and station B807 (latitude -30.18, longitude -51.17, altitude 3.3 m), of the Center for Weather Forecast and Climatic Studies (CPTEC) / National Institute for Space Research (INPE) (http://ftp.cptec.inpe.br/ncep/radiacao_uv/graficoiuv_porto_alegre/). Radiological conditions at the time of the tests are illustrated in Fig. 3.

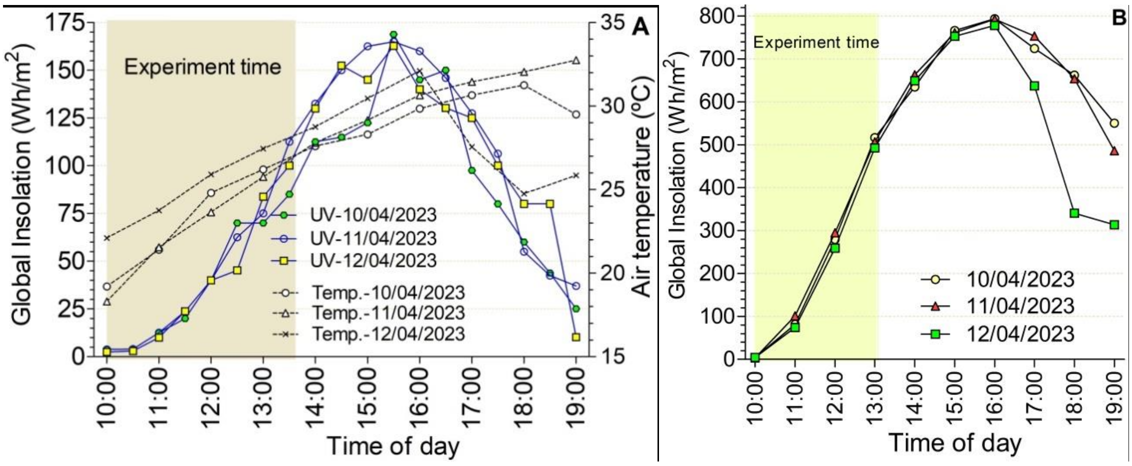

Fig. 3. UV radiation intensity, air temperature (A) and global solar irradiance (B) on the days of the experiment.

We used tap water with a turbidity of 0.5 NTU, which was dechlorinated by adding 4 mg/L of sodium thiosulfate before the experiments. The complete inactivation of residual free chlorine in the water was confirmed using the N,N-diethyl-p-phenylenediamine (DPD) method (APHA, 2005).

The experiments were conducted using water containing all four products simultaneously. Specifically, SMX, DXC, and CBZ were present at a concentration of 1.0 mg/L each, while DXM was at 0.8 mg/L. These tests were repeated three times, once daily for three consecutive days (as shown in Fig. 2).

Duplicate samples were collected for each sampling time (0, 15, 30, 60, 90, and 120 minutes). Control samples were taken at the outlet of the raw water tank. Approximately 100 mL of each sample was collected in a sterile bottle, and 1 mL of 10% formaldehyde was added to preserve it at 4°C until analysis. The water temperature was measured at the treated water outlet nozzle during sampling.

Instrumental analysis

Prior to instrumental analysis, samples were diluted in a ratio of 100 times.

Instrumental analysis was performed through three different methodologies: one for CBZ analysis, other for dexamethasone and the last one for antimicrobials analysis.

For all analysis, the equipment used was a liquid chromatograph Infinity 1290 Series (Agilent Technologies) coupled to a tandem triple quadrupole mass spectrometer API 5000 (Applied Biosystems) using an electrospray probe (ESI) in positive mode as ionization source.

For CBZ analysis, chromatographic separation was performed using a Zorbax Eclipse SB-C18 (Agilent, 150 mm × 4.6 mm, 3.5 μm) LC-column preceded by a Security Guard (Phenomenex) guard column filled with C18 (4,0 × 3.0 mm, 5 μm). The column was used at 40°C. The mobile phase was constituted of (A) water with 0.1% of formic acid and (B) acetonitrile with 0.1% of formic acid. The gradient was initially 95% (A) and 5% (B), which was linearly reverted to 5% of A during 10 minutes, and kept in this condition for 8 minutes. After that, it was changed to 5% of A during 0.5 minutes, and kept in this condition until the end of chromatographic run, at 20 minutes for 6 min, followed by a decrease in phase A to 20% at 11 min and holding for 1 min. The flow rate was set to 0.8 mL/min and the injection volume was 4 µL.

Data acquisition was performed in the multiple reaction monitoring (MRM) mode, selecting the two most abundant product ions for each precursor ion. Source optimized parameters were collision gas = 6 mTorr, curtain gas = 25 mL/min, nebulising gas = 55 mL/min, auxiliary gas = 55 mL/min, capillary voltage = 4.5 kV, and turbo ion spray interface source temperature = 500°C. For CBZ, mass parameters were: precursor ion 192.1; fragment 1 192.1 > 160.1, DP: 40 V; EP: 10 V; CE: 26 V; CXP: 15 V. Fragment 2 192.1 > 132.1, DP: 40 V; EP: 10 V; CE: 41 V; CXP: 15 V.

For DXM analysis, chromatographic separation was performed using a Zorbax Eclipse SB-C18 Rapid Resolution (Agilent, 150 mm × 4.6 mm, 3.5 µm) LC-column also preceded by the same guard column as used for CBZ. Mobile phase was (A) water with 0.1% of formic acid and (B) acetonitrile with 0.1% of formic acid in gradient mode, which consisted in 85% of A during 4 minutes, followed by transition to 65% during 5 minutes, to 55% during 6 minutes. This condition was kept for 5 minutes, then %A returned to 85 at 21 minutes of chromatographic run, finalizing it. The flow rate was set to 0.5 mL/min and the injection volume was 10 µL.

Data acquisition was performed in MRM mode. Source parameters were collision gas = 4 psi, curtain gas = 25 psi, nebulising gas = 55 mL/min, auxiliary gas = 55 mL/min , capillary voltage = 5.5 kV, and turbo ion spray interface source temperature = 600°C.

Mass spectrometry parameters for DXM were: precursor ion 393.2; fragment 1 393.2 > 373.2, DP: 71 V; EP: 10 V; CE: 13 V; CXP: 52 V. Fragment 2 393.2 > 355.3, DP: 71 V; EP: 10 V; CE: 15 V; CXP: 46 V.

For the analysis of SMX and doxycycline, the column used in chromatographic separation was Venusil (Agella, 100 mm × 2.1 mm, 3 µm), preceded by the same guard column as in the other methodologies described above. Mobile phase consisted of (A) water 0.1% formic acid 5mM ammonium formiate and (B) methanol 0.1% formic acid 5 mM ammonium formiate. Gradient was maintained in 95% of A during 3 minutes, then passed to 0% of A at 6 minutes of analysis, condition maintained for 3.5 minutes, and then returned to 95% of A at 10 minutes of analysis, which was kept for 1 minute, until the end of chromatographic run. The flow rate was set to 0.3 mL/min and the injection volume was 10 μL.

Data acquisition was performed in MRM mode. Source parameters were collision gas = 4 psi, curtain gas = 25 psi, nebulising gas = 55 mL/min, auxiliary gas = 55 mL/min, capillary voltage = 5.5 kV, and turbo ion spray interface source temperature = 600°C.

Mass spectrometry parameters for DXM were: precursor ion 393.2; fragment 1 393.2 > 373.2, DP: 71 V; EP: 10 V; CE: 13 V; CXP: 52 V. Fragment 2 393.2 > 355.3, DP: 71 V; EP: 10 V; CE: 15 V; CXP: 46 V.

Mass spectrometry parameters for SMX were precursor ion; 254.0; fragment 1 254.0 > 156.0, DP: 71 V; EP: 10 V; CE: 23 V; CXP: 22 V. Fragment 2 254.0 > 92.0, DP: 71 V; EP: 10 V; CE: 35 V; CXP: 14 V.

For DXC, mass parameters were precursor ion 445.2; fragment 1 445.2 > 428.0, DP: 121 V; EP: 10 V; CE: 15 V; CXP: 54 V. Fragment 2 445.2 > 154.0, DP: 121 V; EP: 10 V; CE: 35 V; CXP: 18 V.

Data analysis

The data were represented as an average and then converted into percentages, considering the values of sample replicates and their respective repetitions, with standard deviation calculated at a 95% confidence level. Graphs were generated using the GraphPad Prism 8.02 software.

Results

The chromatograms of the untreated controls for each of the four tested products are presented in Fig. 4. The control values were compared with the values obtained from treated samples for the corresponding product.

Fig. 5 presents the dynamics of simultaneous degradation of the drugs DXC, SMX, DXM, and the agro-fungicide CBZ. The data reveal a rapid decline in the concentration of DXC, with more than an 87% reduction after just 15 minutes of exposure. Similarly, the other products also exhibited decreases in concentration, although at a relatively slower rate: 35.5%, 32%, and 31.8% for SMX, DXM, and CBZ, respectively.

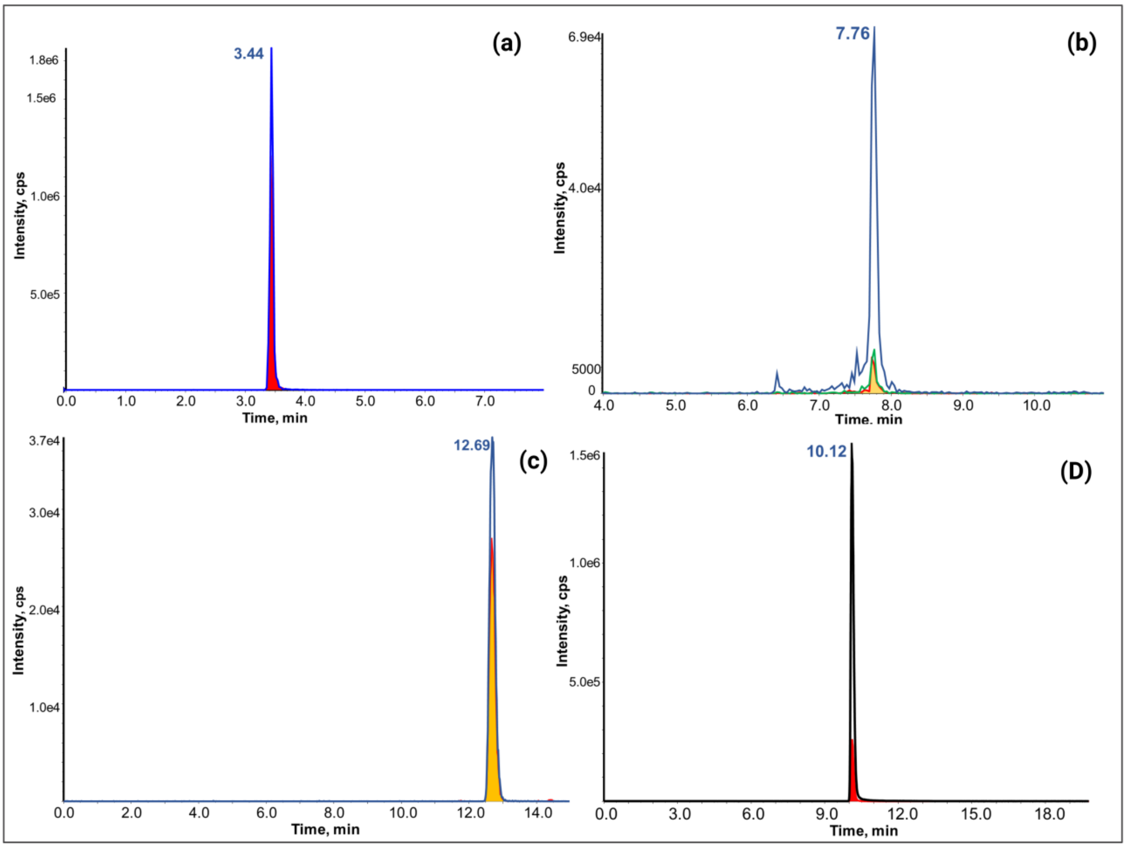

Fig. 4. Chromatograms obtained by LC-ESI-MS/MS for sulfamethoxazole – SMX (a), doxycycline – DXC (b), dexamethasone – DXM (c) and carbendazimc – CBZ (d).

The concentrations of all products appeared to stabilize between 15 to 30 minutes, followed by a significant decline after 60 minutes of exposure, with reductions of 90.8%, 49.3%, and 58% for DXC, DXM, and CBZ, respectively. Surprisingly, samples collected after 60 minutes showed a slight reduction in SMX concentration (12.6%).

It's worth noting that the water temperature gradually increased, reaching more than 70°C after 2 hours of retention.

The system productivity was approximately 101 L of processed water per day, considering the capacity of 1.06 L of each of the three reactors, 8 h of system operation and 15 minutes of retention per sequential batch.

DISCUSSION

The growing volume of research and the maturation of photocatalytic technologies utilizing solar radiation for water contaminant degradation highlights the need to develop solar reactors capable of integrating photocatalysts. These reactors need to be designed in a way that makes them applicable to processing substantial volumes of water in real-life situations.

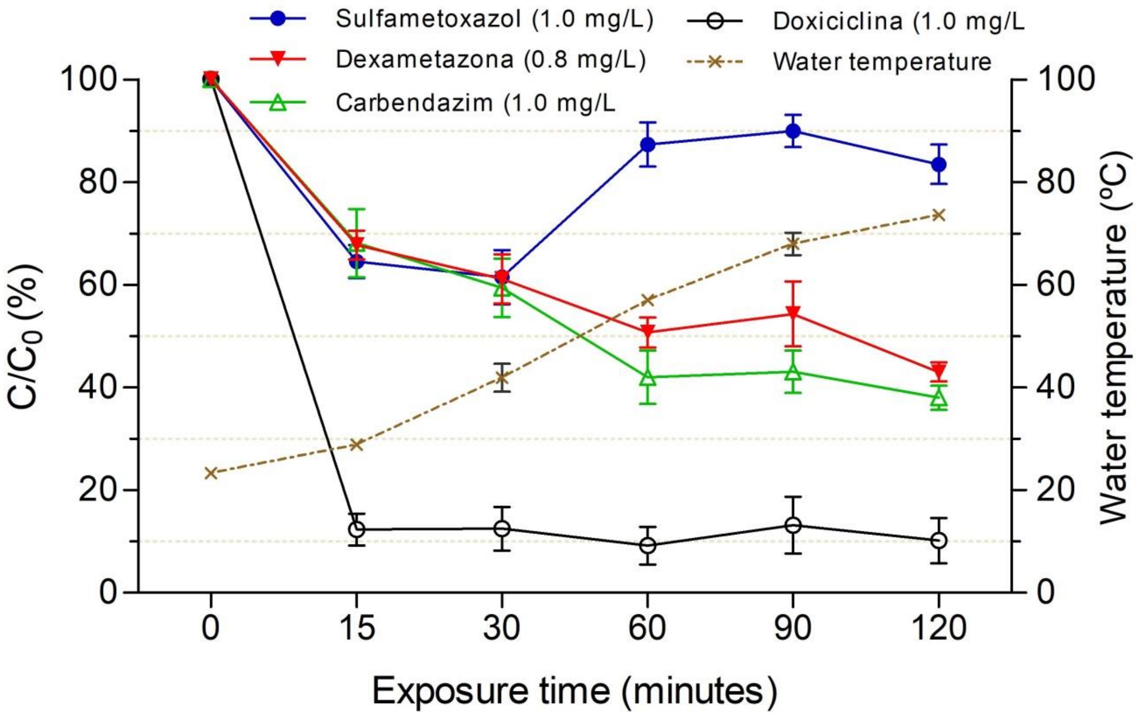

Fig. 5: Dynamics of photocatalytic degradation of doxycycline - DXC, sulfamethoxazole – SMX, dexamethasone – DXM and carbendazim – CBZ in water.

The present work reports the initial findings from developing and testing a pilot system designed for the continuous-flow photocatalytic degradation of pharmaceuticals and pesticides in water, employing TiO_2 as the photocatalyst. While the current version of the system has undergone testing in intermittent flow, the primary objective of its development is to establish its functionality in continuous flow. Therefore, this discussion primarily focuses on the results obtained within the shortest exposure time of 15 minutes.

The remarkable 90% reduction in DXC concentration (Fig. 5) after just 15 minutes of system focusing suggests a promising capability for processing larger volumes of water. This degradation is primarily attributed to the UV-mediated photocatalytic effect of TiO_2. It's worth noting that previous studies have established that the impact of visible sunlight radiation (with or without

TiO_2), as well as UV-A, B, and C radiation, on DXC within such a short exposure time is negligible (Yun et al. 2018; Berdini et al. 2022; Li et al. 2023). Previous research has shown that the photodegradation of DXC (0.06 mg/L, 100 mL) by UV-C radiation (254 nm, intensity 3216 μW/cm^2) alone over 6 hours is minimal (5%). However, in the presence of TiO_2, the degradation efficiency significantly increases to 86%, with 22% mineralization (Berdini et al. 2022). The literature also describes the intermediate products formed during the photocatalytic degradation of tetracyclines, including DXC, using TiO_2 (Huang and Liu, 2023). The significantly higher degradation rate of DXC, even in the presence of multiple contaminants and at a relatively higher concentration, within the short time frame observed in our system, strongly emphasizes its substantial potential for practical applications in chemical water decontamination scenarios.

The findings (Fig. 5) demonstrate that the degradation of SMX after just 15 minutes of exposure reached 35.5%. Similar to the case of DXC, the degradation of SMX is primarily attributed to the photocatalytic action of TiO_2 induced by UV radiation. This assertion is supported by prior research, which has consistently demonstrated that exposure of SMX to visible light (with or without TiO_2) and UV-A radiation alone yields negligible degradation rates, often remaining below 13%, even after extended exposure periods of up to 7 hours (Hu et al. 2007; Bui et al. 2022).

Our findings align with numerous studies in the literature, which have reported photocatalytic degradation rates ranging from 13% to ~55% within a 15-minute timeframe. For instance, was observed that when SMX (100 μM) was exposed to UV-A radiation in the presence of TiO_2 (0.1 g/L), it exhibited photocatalytic degradation exceeding 55% within just 15 minutes (with complete degradation achieved after 60 min at 25°C) (Hu et al. 2007). Was also observed that, unlike under anoxic conditions which inhibit the photocatalytic degradation of SMX, air-sparging or O_2-sparging promotes degradation (Hu et al. 2007). Other authors achieved approximately 15% degradation of SMX (100 mg/L) in the presence of TiO_2 (1000 mg/L) and simulated solar UV radiation (λ >290 nm) (Abellán et al. 2007). The degradation of ~15% of SMX (25 mg/L, 250 mL, flow rate: 0.22 L/min, 25°C) in the presence of TiO_2 and UV-A (365 nm) after a 15-minute reaction period was also reported (Ahmed et al. 2014). Similarly, was reported about 13% degradation of SMX (5 mg/L) using TiO_2 (700 mg/L) and UV-C radiation (254 nm) during a 15-minute reaction (Akter et al. 2022). In a study conducted by Bui et al. (2022), a Pyrex tubular reactor (250 × 10 mm) was utilized, housing a TiO_2-ceramic monolith and exposed to UV-A radiation from lamps. This setup resulted in a degradation of less than 25% of SMX (5 mg/L, 500 mL, recirculation flow set at 50 mL/min). Notably, the degradation rate was found to be inversely proportional to the initial concentration of SMX, with higher degradation rates observed at lower initial concentrations (0.5 – 20 mg/L). Additionally, this degradation process showed optimal performance across a pH range from 2 to 7. The isolated effect of pH on degradation appeared to be negligible.

The intermediate compounds formed during the photocatalytic degradation of SMX by TiO_2 are described in recent literature (Bui et al. 2022).

It is worth noting that most results reported in the literature have been obtained through controlled studies, which typically involve smaller volumes of water, intense and constant UV radiation, and solutions contaminated solely by SMX. In contrast, our present study utilized a significantly larger volume of tap water (~3 L per sequential batch) that was simultaneously contaminated by four different products. Moreover, instead of artificial UV sources, we harnessed natural sunlight as our radiation source. These distinctions highlight the considerable potential of our system.

The data (Fig. 5) indicate that after 15 minutes of reaction, the degradation of DXM was 32%. This degradation can be primarily attributed to the combined effect of solar UV and photocatalysis by TiO_2. Notably, when DXM (15 mg/L) was exposed to visible light, with or without TiO_2, it resulted in only a negligible concentration reduction (>4%) (Pazoki et al. 2016). Our findings align with the literature reporting ~30% photodegradation of DXM (50 µg/50 mL) after 15 minutes of exposure to natural solar radiation, with complete photodegradation occurring after 2 hours (Kawabata et al. 2013). In contrast, our results differ from the findings of Calza et al. (2001), who reported complete photocatalytic degradation of DXM (10 mg/L) in the presence of TiO_2 (200 mg/L) and UV-A radiation (340–400 nm) after 15 minutes of reaction.

While increasing temperature variations (between 30 and 35^{o}C) enhanced the photocatalytic degradation of DXM (15 mg/L) by TiO_2, further increases up to 85°C had the opposite effect. This inhibition has been attributed to a reduction in the adsorption capacity of organic compounds to oxygen (Pazoki et al. 2016). Our data do not suggest a significant contribution of temperature variation to the degradation rate of DXM or any other product.

The by-products generated during the solar photodegradation of DXM, particularly under UV-B irradiation, exhibited toxicity to *Photobacterium phosphoreum*, a model organism for aquatic life. In contrast, the non-irradiated control by-products were non-toxic (Kawabata et al. 2013). The transformation products resulting from DXM degradation, including those through TiO_2-mediated photocatalysis, have been previously documented (Quaresma et al. 2021; Calza et al. 2001).

After 15 minutes, the concentration of CBZ showed a decline of 31.8% (Fig. 5). This reduction was primarily attributed to the photocatalytic effect of TiO_2 induced by solar UV radiation, since previous studies have reported that solar radiation (or UV-A) alone has a negligible effect on CBZ degradation (0-7%), even after 4-5 hours of exposure (Machado et al. 2022; Kaur et al. 2016). In a study by Kaur et al. (2018), using a flat-plate photocatalytic reactor incorporating TiO_2 immobilized on clay beads archived less than 10% degradation of CBZ (8 mg/mL) within 25 minutes of photocatalysis under natural sunlight. Similarly, in a laboratory test conducted by Singh et al. (2018), approximately 5% degradation of CBZ (10 mg/L, 200 mL) was achieved when exposed to TiO_2-coated cement beads and UV-A radiation (365 nm, intensity 25 W m-2) for approximately 15 minutes. In laboratory tests, a degradation of 70% of CBZ was achieved in 3 hours, whereas in pilot tests utilizing natural solar radiation, the same reduction took 10 hours. A substantial degradation rates of CBZ (between ~35% and 75%) after just 15 minutes of TiO_2-based photocatalysis under natural sunlight, with total UV intensities ranging from 3.6 to 4.2 mW/cm², was archived by Mungsuk et al. (2023). This study found that higher degradation rates were associated with higher TiO_2 concentrations and temperatures (ranging from 29.5 to 37.6 °C). While an increase in temperature has been identified as an accelerating factor for TiO_2 photocatalysis in other studies (Liu et al. 2019; Rahman et al. 2023), our data suggest that the contribution of thermal variation was not pronounced. This aligns with the literature reporting that temperature adjustments between 15 to 45°C resulted in only a modest increase (<8%) in the photocatalytic degradation efficiency of CBZ using TiO_2 (Saien and Khezriajoo, 2008). It has also been noted that pH values in the range of 6 to 6.3, slightly acidic to close to neutral, are favorable for the photocatalytic degradation of CBZ by TiO_2 (Kaur et al. 2018; Rajeswari and Kanmani 2009). Moreover, the transformation products of CBZ photocatalytic degradation have been described in the literature (Kaur et al. 2018).

The literature evidence presented above underscores the system's substantial potential for degrading CBZ. This potential is particularly noteworthy because TiO_2 is immobilized within the reactor (not suspended), reducing the contact surface, and enabling the simultaneous degradation of CBZ and three other products.

Structural improvements

Overall, the developed system holds significant potential for practical use in chemical water decontamination, primarily due to the lower concentrations of contaminants found in real polluted water. Nevertheless, further structural enhancements in the system configuration are necessary to address existing challenges. These challenges include:

(1) Preventing cross-contamination between the water in the reactor and the raw water still in the pipes during water retention. This contamination may account for the unexpected observation that complete degradation of the products was not achieved, even after extended retention times (Fig. 5). It is essential to note that double retention (before entering and after leaving the reactors) should be avoided, as it can lead to a greater increase in pressure due to the heating and expansion of the water, and the risk of reactor rupture.

(2) Eliminating the requirement for water retention is desirable, as it not only increases the volume of treated water but also mitigates the risk of pressure increase inside the reactor, which can lead to ruptures and leaks. During experiments, overheating caused challenges, including leaks due to broken reactor connectors.

The limitations (1 and 2) can be overcome by establishing water processing in continuous flow, ensuring that the water transit time through the reactors is >15 minutes; the increase in the number and extent of reactors, in this case, are valuable changes. Furthermore, increasing the radiation collection area is desirable to increase the radiation available.

The integration of Fresnel-type solar collectors arranged in a truncated delta design could be an interesting approach. Additionally, structural improvements to the large-scale solar water disinfection systems discussed in our previous study can be explored (Chaúque et al. 2022). Furthermore, it is desirable to consider including a step to improve water oxygenation before entering the reactors.

Functional enhancements

Although the present work has a primarily structural focus, the performance of the system described here can be substantially increased through the integration of functional improvements.

Complex photocatalysts, such as those composed of TiO_2 combined with other elements or substances, show promise in enhancing the degradation performance of drugs and other contaminants. This improvement is achieved through the increased production of reactive oxygen species (ROS), including the possibility of also utilizing visible light. For example, in a study by Kubiak et al. (2023), a box reactor equipped with LED lamps emitting UV-A (365-400 nm) and visible light (400-420 nm) was used to degrade a SMX solution (20 mg/L, 100 mL) in the presence of TiO_2 (100 mg) or TiO_2-graphite (TiO_2-G). After 15 minutes of reaction, degradation rates ~<15% and ~30% were observed with TiO_2 and TiO_2-G, respectively. Using TiO_2 or TiO_2-G, degradation levels reached approximately 90% and 100%, respectively, after 180 minutes of reaction. Other researchers reported 26% degradation of SMX (25 mg/L, 300 mL) when using UV-C and TiO_2 (100 mg/L) after 15 minutes of reaction. However, when $Ce_{0,8}Gd_{0,2}O_{2-\delta}/TiO_2$ was employed as a photocatalyst under the same exposure time, a significantly higher degradation rate of ~57% was achieved (Rodrigues et al. 2019). After 120 minutes of reaction, ~79% and ~98% were degraded using TiO2 and $Ce_{0,8}Gd_{0,2}O_{2-\delta}/TiO_2$, respectively (Rodrigues et al. 2019). In contrast, Mertah et al. (2023) reported ~46% degradation of SMX (5 mg/L, 150 mL) within 15 minutes using simulated solar radiation ($\lambda \leq 290$ nm, 600 W/m2) and TiO_2 (250 mg/L), therefore using CuS-

TiO2 degradation was < 30% was obtained. Complete degradation took <100 minutes with TiO_2 and <125 minutes with CuS-TiO_2.

Integrating photocatalysts capable of utilizing ultraviolet and visible sunlight is advantageous and desirable. For example, Li et al. (2023) developed ultrathin TiO_2(B) nanosheets with abundant oxygen vacancies (TiO_2(B)-OVs) for photocatalysis using visible light. They achieved ~34% degradation of DXC (20 mg/L, 100 mL) with TiO_2(B)-OVs (200 mg/L) compared to ~12% using TiO_2, under visible light for 15 minutes reaction (Li et al. 2023). The exploitation of hierarchical ternary TiO2/graphene quantum dot/ZIF-8 nanocomposite was also reported to be a promising mechanism for utilizing visible light for DXC photocatalysis (Rabeie and Mahmoodi, 2023).

Combining complex TiO_2 or TiO_2-based photocatalysts with other materials with relevant properties, such as adsorption, is a highly promising approach.

It has been demonstrated that combining the adsorptive properties of biochar (pBC) with the photocatalytic properties of TiO_2 improves the removal of SMX (10 mg/L) in the presence of UV radiation. As a result, the removal efficiency of SMX by pure TiO2 (58%) was surpassed by that of TiO_2/pBC (91%) (Zhang et al. 2017). Furthermore, the degradation of SMX using biochar/TiO_2 enhanced and alsoenhanced efficacy, resulting in an effluent with negligible toxicity (Kim and Kan 2016).

Conclusions

- A solar system designed for the photocatalytic decontamination of water in continuous flow using TiO_2 was developed and successfully tested, initially in intermittent flow with 15-minute batches, for the degradation of pharmaceutical products (DXC, SMX, DXM) and an agrofungicide (CBZ).
- The simultaneous degradation rates of DXC, SMX, DXM, and CBZ after 15 minutes of retention were 87%, 35.5%, 32%, and 31.8%, respectively.
- A daily productivity of 101 L of processed water can be achieved in sequential batch operation with a 15-minute retention time.
- The system holds great potential to be applied in real situations of chemical water decontamination.

- Structural improvements are necessary to establish continuous-flow operation for the system. These improvements may involve increasing the number and size of reactors, and the solar radiation collection area.
- Functional improvements are highly desirable, and they should encompass the integration of more potent photocatalytic materials capable of utilizing both UV and visible solar radiation. Additionally, integrating adsorbents with the capacity to reduce the toxicity of byproducts is also important.

Ethical Approval

Not applicable.

Consent to Participate

Not applicable.

Consent to publish

Authors give consent to publish this work in journal 'Environmental Science and Pollution Research' by Springer publisher.

Authors contributions

Beni Jequicene Mussengue Chaúque: conceptualization, methodology, formal analysis and investigation, original draft preparation, review and editing. Louise Jank: methodology, investigation, original draft preparation. Antônio Domingues Benetti: review, resource, supervision. Marilise Brittes Rott: review, resource supervision.

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Competing interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

All data are given in the manuscript.

Declarations Ethical approval

The authors declare that this work has not been published elsewhere and that it has not been submitted simultaneously for publication elsewhere.

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5. DISCUSSÃO GERAL

A água é um recurso primário à existência da vida, incluindo a dos humanos. E a sua qualidade microbiológica é determinante para a dinâmica da epidemiologia das doenças gastrointestinais relacionadas á água potável, bem como das diferentes doenças associadas ao seu uso recreativo. Os diferentes estudos descritos na presente tese, essencialmente visaram: (1) contribuir para ampliar a compreensão cada vez melhor sobre o papel da água na transmissão de doenças, bem como (2) sobre os métodos acessíveis (especialmente a SODIS) de aprovisionamento de água biologicamente segura e seu impacto para saúde. Também buscaram (3) examinar o desempenho da SODIS convencional sobre cistos de *A. castellanii* e sobre bactérias (*P. aeruginosa*) internalizadas; além de (4) descrever a construção e teste de um sistema de desinfeção solar de água em fluxo contínuo na inativação de estruturas de persistência ambiental (cistos, oocistos, esporos) de *Acanthamoeba*, *Cryptosporidium* (dados não publicados) e *Bacillus*. A construção e teste de um sistema de remoção fotocatalítica de fármacos e agrotóxico na água também foi descrita.

Os achados mostram que a prevalência global de AVL na água usadas para fins de recreação (incluindo piscinas e águas superficiais) é alta (44.34%), incluindo a prevalência dos gêneros de AVL mais frequentemente reportados em casos de doenças, nomeadamente *Acanthamoeba* spp. (33.47%) e *Naegleria* spp. (30.95%) (Milanez et al., 2022; Angelici et al., 2021). Importa destacar que a prevalência global de AVL é também alta em piscinas (que se pressupõe que seja tratada) variando entre 46 a 52%. Estes resultados indicam claramente que o risco para saúde nestes ambientes é alto, e que há necessidade de desenvolver métodos eficazes de desinfecção que sejam igualmente acessíveis e de fácil uso na prática. Além disso, os resultados apontam que há necessidade de um monitoramento constante pela vigilância sanitária e o aprimoramento de mecanismos de diagnóstico célere e tratamento de doenças causadas pelas AVL.

A bem estabelecida atuação das células amebianas (AVL) como abrigo, local de proliferação, e estoque ambiental de diferentes vírus

(Rayamajhee et al., 2021) incluindo os vírus respiratórios (Day et al., 2021), combinada com a onipresença e abundância de AVL nos corpos de água incluindo nas águas residuais onde igualmente são detectadas densidades substanciais de partículas virais de Sars-Cov-2 (10^6 - 10^{11} (Xiao et al., 2020)). Indica que há altas chances de interação destes microrganismos no ambiente, há também fortes chances de que desta interação ocorra à persistência ambiental do vírus no ambiente, como demostrado para um substituto de Sars-Cov-2 (Dey et al., 2021). Além disso, as partículas virais liberadas pelas amebas, dentro de vesículas apresentam maior estabilidade e persistência ambiental além da relatada (4 – 6 dias (Giacobbo et al., 2021)), o que por sua vez aumenta as chances da contaminação fecal oral pelo vírus. As chances da contaminação fecal oral se aumentam ainda pelo facto de as partículas infeciosas deste vírus serem detectadas nas fezes e, ainda pelo facto do Sars-Cov-2 ser capaz de multiplicar ao longo do trato digestivo (Yao et al., 2020). Todos estes fatos apontam de forma clara a necessidade de se realizar estudos visando elucidar as implicações da interação das AVL e Sars-Cov-2, além de, sobretudo mostrarem a necessidade de se tratar a água potável. É importante mencionar de que a SODIS é efetiva contra vírus incluindo Sars-Cov-2.

A SODIS convencional, apesar de eficaz apresenta um conjunto de limitações, que incluem o baixo volume de água tratada, recalcitrância de certos microrganismos, alta turbidez da água bruta, natureza intermitente da disponibilidade da luz solar, e a baixa aceitabilidade social. A superação de cada uma destas limitações exigem aprimoramentos em nível dos reatores SODIS, que incluem, o uso de materiais de melhor rendimento fototérmico, boa resistência e durabilidade. Além disso, a integração de diferentes tecnologias para o pré e pós-tratamento da água, por exemplo, para reduzir a turbidez da água e, evitar a re-contaminação ou recrescimento microbiano é também desejável. O melhoramento da configuração, mecanismo de funcionamento, integração de tecnologias para aceleração da inativação microbiana (UV, absorvedores de calor, nanomateriais, etc) são outros aprimoramentos em nível de dispositivos de SODIS que possibilitarão a superação da baixa produtividade e aceitação social, além de manter a eficácia e produtividade em dias de baixa insolação.

O uso da SODIS como uma estratégia de fornecimento de água potável em larga escala passa pelo desenvolvimento de sistemas de SODIS de alto desempenho que operam em fluxo contínuo ou intermitente. Estes sistemas precisam operar utilizando o efeito sinérgico do calor, e radiação ultravioleta solar; além disso, a integração de as tecnologias baseadas em nanomateriais fototérmicos e fotocatalíticos para acelerar o processo de inativação microbiana e/ou aumentar a produtividade precisa ser considerada. Estes sistemas podem ser desenvolvidos mediante a combinação de diferentes projetos de sistemas de SODIS atualmente disponíveis e/ou aprimorando os mesos. Os aprimoramentos incluem a maximização do rendimento dos coletores solares (com enfoque para os do tipo concentrador) bem como do desempenho dos reatores que farão o uso da energia disponibilizada pelos coletores solares.

O uso consistente da SODIS em escala comunitária, nos contextos de comunidades desprivilegiadss quanto ao acesso a fontes seguras de água potável, leva à redução do risco e prevalência de doenças diarreicas. A redução de diarreias se deve tanto pela ingestão de água sem patógenos viáveis quanto à indução de mudanças imunológicas protetivas motivada pela ingestão de patógenos inviáveis, porém imunologicamente ativos (Ssemakalu et al., 2015, 2021), especialmente durante os surtos (Ssemakalu et al., 2014).

As barreiras, facilitadores bem como as estratégias de entrega para o sucesso de tecnologias de baixo custo de tratamento domiciliar de água potável (SODIS, Cloração, Floculação-Desinfecção, filtros lentos de areia e Filtro de Cerâmica) foram investigados neste trabalho. Um número equiparável de barreiras (77) e facilitadores (76) foram identificados e a maioria destas se enquadra no domínio, psicossocial (37,7, 47,4%), promoção (22,1, 26,3%), tecnologia (28,6; 10,5%), respectivamente. As estratégias de entrega das tecnologias que foram identificadas incluem principalmente a educação sobre segurança da água potável e promoção da tecnologia em si, treinamento sobre o uso da tecnologia, doação ou venda promocional, assistência técnica e uso de um diário médico para controle caseiro de episódios de diarreias. Todas as barreiras e facilitadores identificados interferem na adoção inicial, uso regular e uso sustentado de todas as tecnologias de tratamento domiciliar de água potável e precisam ser consideradas no planejamento e na condução das intervenções para melhorar a segurança da água. A análise de dados sugere que os impactos na saúde das intervenções de melhoria da segurança da água potável diminuíram com o aumento do tempo desde a adoção inicial das tecnologias. O treinamento adequado dos usuários e a doação das tecnologias, combinados com alta adesão, são importantes preditores de sucesso para intervenções baseadas em tecnologias de baixo custo de tratamento domiciliar de água potável. De modo geral, as limitações relatadas para todos os tipos de tecnologias descritas podem ser superadas identificando (e/ou criando) e explorando os facilitadores listados no capítulo VI.

A efetividade da SODIS convencional sobre a viabilidade de cistos de *A. castellanii* e *P. aeruginosa* internalizadas nos cistos foi realizada, expondo-se a água contaminada engarrafada durante 8 h/dia à luz solar forte por até 3 dias consecutivos. A SODIS foi ineficaz em inativar tanto os cistos de *A. castellanii* bem como *P. aeruginosa* internalizada, mesmo após 24 horas cumulativas de exposição solar. Embora o uso da SODIS convencional como estratégia de aprovisionamento de água potável segura pelas comunidades deva continuar sendo encorajado, a água descontaminada com SODIS deve ser consumida dentro de três dias.

O sistema de desinfecção solar de água em fluxo contínuo por fervura (3 ± 92ºC) seguido de exposição à radiação UV (por 25 - 45 s), desenvolvido com base no aprimoramento da versão anterior do sistema previamente publicada por nosso grupo de pesquisa, se mostrou eficaz na inativação de cistos de *A. castellanii* (1,38 x10^3 cistos/L), e esporos de *Bacillus altitudinis* (10^2 UFC/mL). O sistema alcançou uma produtividade de 240 a 360 L/dia de água tratada, operando por 8 horas. O sistema tem potencial de ser utilizado no abastecimento de água potável em escala comunitário e sua produtividade ainda pode ser aumentada mediante adoção dos aprimoramentos descritos no pedido de patente (número BR 102022026159-8) depositado no INPI.

O sistema de desinfecção solar de água em fluxo contínuo alterado por meio da integração de fotocatalizador TiO_2, e testado para degradar simultaneamente fármacos e agrotóxico na agua mostrou-se promissor. Sendo capaz de degradar DXC (87%), SMX (35,5%) DXM (32%) e CBZ (31,8%) em apenas 15 minutos. Deste modo o sistema mostrou não apenas uma boa eficácia, mas também uma produção diária substancial (101 L) de água processada. É importante notar que a concentração inicial dos produtos (1mg/L) testados é muito mais alta do que a encontrada nos diferentes corpos de água reais, e isso, sugere que em situações reais de descontaminação de água uma eficácia de ~100% de degradação de contaminantes pode ser alcançada pelo sistema. O sistema tem potencial de ser aplicado em situações reais de descontaminação química de água, e os aprimoramentos adicionais que permitam a sua operação de fluxo contínuo, bem como a integração de adsorventes e materiais fotocatalíticos de alto desempenho podem melhorar significativamente o desempenho do sistema.

6. CONCLUSÕES

O trabalho desenvolvido do qual resultou a presente tese caracterizou-se pela realização de diferentes estudos de revisão crítica, revisão sistemática com ou sem meta-análise, e estudos experimentais resultando na produção de 18 artigos (9 do quais já detalhados e os restantes em apêndices I-IX) e um depósito de pedido de patente (Apêndice X). Dos referidos estudos resultaram as seguintes conclusões:

A prevalência de AVL em águas usadas para recreação (piscinas e água superficiais) é alta, e existe um risco de infecção por patógenos amebianos e não amebianos (carreados pelas AVL).

O desenvolvimento e implementação de técnicas de desinfecção eficazes contra AVL aplicáveis à água destinada aos ambientes de recreação artificial é necessário.

O monitoramento da segurança das águas superficiais usadas para recreação e sinalização em caso de risco, bem como a alocação de profissionais treinados e em prontidão em áreas de risco é fortemente recomendado.

Estudos voltados para a segurança microbiológica da água usada para fins recreativos ou potáveis precisam considerar avaliar a interação in situ e in vitro de diferentes vírus de importância médica, incluindo, Sars-Cov-2 com AVL.

Sistemas de SODIS operando em fluxo contínuo ou intermitente de grande vazão podem ser usados no aprovisionamento público em larga escala de água potável segura a baixo custo.

O uso consistente da SODIS em escala comunitário resulta na redução significativa do risco e prevalência de doenças gastrointestinais de transmissão hídrica, como as diarreicas. Estes ganhos epidemiológicos resultam da melhoria da segurança (microbiológica) da água potável, bem como pela indução de mudanças imunológicas protetivas em usuários da SODIS (especialmente durante os surtos).

O sucesso ou insucesso do uso das tecnologias de baixo custo de tratamento domiciliar de água, na prevenção ou combate às doenças de transmissão hídrica é predominantemente determinado por barreiras e facilitadores enquadrados nos domínios psicossocial, promocional e tecnológico.

As barreiras e facilitadores (psicossociais, promocionais e tecnológicas) interferem na adoção inicial, uso regular e uso sustentado de todas tecnologias de baixo custo de tratamento de água potável no ponto de uso.

O treinamento adequado dos usuários e a doação das tecnologias, combinados com alta adesão, são importantes preditores de sucesso para as intervenções baseadas em tecnologias de baixo custo de tratamento domiciliar de água potável no combate às doenças de transmissão hídricas.

A SODIS convencional nas condições de sol natural real é incapaz de inativar tanto os cistos de *A. castellanii*, e bactérias (*P. aeruginosa*) abrigadas no interior dos cistos. Embora o uso da SODIS pelas comunidades deva continuar sendo encorajado, a água desinfetada por SODIS convencional deve ser consumida dentro de três dias, devido ao risco de re-colonização da água por bactérias carreadas pelos cistos das AVL.

O sistema piloto de desinfecção solar de água em fluxo contínuo desenvolvido é eficiente na remoção de microrganismos recalcitrantes (cistos de AVL, esporos de *Bacillus altitudinis*) da água, e alcançado uma produção de um volume consideravelmente alto de água potável segura, por isso, tem potencial de ser utilizado no abastecimento de água potável larga escala.

O sistema solar piloto de degradação fotocatalítica simultânea de fármacos e agrotóxicos desenvolvido tem potencial de ser aplicado em situação real de descontaminação química de água.

Assim, os resultados desta Tese garantem que é possível fornecer água segura, mediante a exploração de métodos alternativos baseados na radiação solar para inativação de microrganismos e degradação fotocatalítica de fármacos e agrotóxicos.

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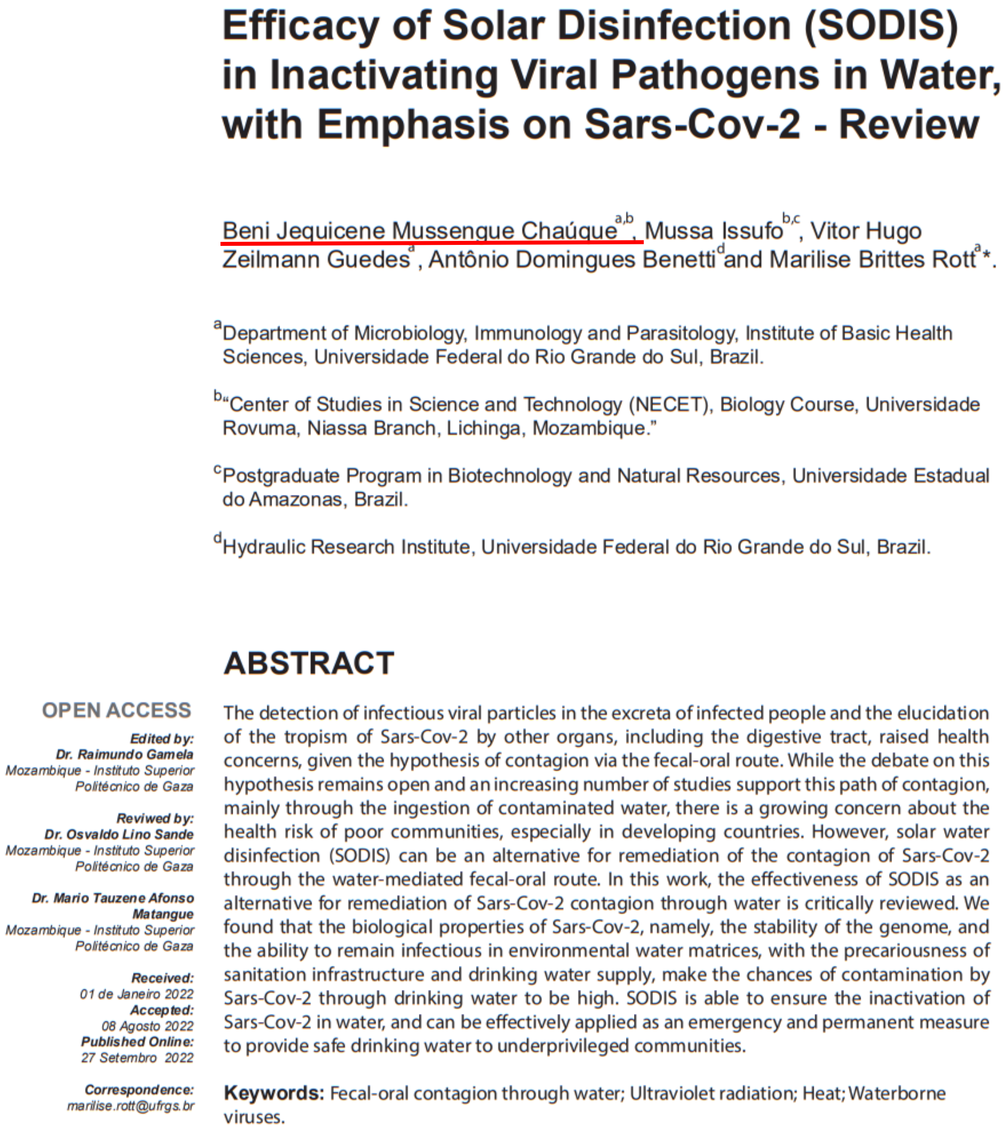
APÊNDICE I

Artigo intitulado “Efficacy of Solar Disinfection (SODIS) in Inactivating Viral Pathogens in Water, with Emphasis on Sars-Cov-2 - Review” publicado em 27 setembro de 2022 na revista Mozambican Journal Of Applied Sciences. https://doi.org/10.53224/mjas/ispg/2022v1n7. É uma revisão critica sobre a eficácia da SODIS na inativação de vírus de transmissão hídrica, incluindo o Sars-Cov-2. Embora não se tenha estabelecido ligação entre sintomas de Covid-19 e a contaminação oral mediada pela água, sua presença em diferentes corpos de água, incluindo a água potável está amplamente documentado.



Efficacy of Solar Disinfection (SODIS) in Inactivating Viral Pathogens in Water, with Emphasis on Sars-Cov-2 - Review

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ABSTRACT

The detection of infectious viral particles in the excreta of infected people and the elucidation of the tropism of Sars-Cov-2 by other organs, including the digestive tract, raised health concerns, given the hypothesis of contagion via the fecal-oral route. While the debate on this hypothesis remains open and an increasing number of studies support this path of contagion, mainly through the ingestion of contaminated water, there is a growing concern about the health risk of poor communities, especially in developing countries. However, solar water disinfection (SODIS) can be an alternative for remediation of the contagion of Sars-Cov-2 through the water-mediated fecal-oral route. In this work, the effectiveness of SODIS as an alternative for remediation of Sars-Cov-2 contagion through water is critically reviewed. We found that the biological properties of Sars-Cov-2, namely, the stability of the genome, and the ability to remain infectious in environmental water matrices, with the precariousness of sanitation infrastructure and drinking water supply, make the chances of contamination by Sars-Cov-2 through drinking water to be high. SODIS is able to ensure the inactivation of Sars-Cov-2 in water, and can be effectively applied as an emergency and permanent measure to provide safe drinking water to underprivileged communities.

Keywords: Fecal-oral contagion through water; Ultraviolet radiation; Heat; Waterborne viruses.

APÊNDICE II

Artigo intitulado “Occurrence of *Naegleria fowleri* and their Implication for Health - a Look Under the One Health approaches” publicado em 25 de outubro de 2022 na revista International Journal of Hygiene and Environmental Health. https://doi.org/10.1016/j.ijheh.2022.114053. O artigo é uma revisão crítica com meta-análise que analisa a ocorrência ambiental de *N. fowleri* e o risco para a saúde sob perspectiva da saúde única.

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Occurrence of *Naegleria fowleri* and their implication for health - a look under the One Health approaches

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ARTICLE INFO

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One health
Primary amoebic meningoencephalitis
Climate change
Global warming
Free-living amoebae

ABSTRACT

One Health approaches are becoming increasingly necessary in the world we live in. Human beings, animals, plants and the environment are intrinsically interconnected and when some intervention occurs, mainly through the action of man himself, everyone suffers the consequences. The objective of this review was to collect data about the occurrence and dispersion of *Naegleria fowleri*, an amphizoic free-living amoeba, and its implications for health approaches through the One Health concept. *N. fowleri* is an opportunistic amoeba, better known as brain-eating amoeba, which causes Primary Amoebic Meningoencephalitis. This amoeba is widely distributed around the world, being isolated from different matrices of natural or anthropogenic environments with temperatures above 30 °C with an upper limit of 45–46 °C. Highly lethal, it has claimed numerous humans patients and only five people have survived the disease so far. Our results indicate that climate change plays a major role in the growth and dispersion of the pathogen in the environment, causing damage to humans and animals. Changes in temperature, antimicrobial resistance, possible transport of other microorganisms by the amoeba, conventional treatments with chlorination, among others, were addressed in our study and should be considered in order to raise questions and possible solutions to this problem that involves health as a whole. The diagnostic methods, prospection of new anti-*Naegleria* drugs and the control of this parasite in the environment are specific and urgent issues. We know that the human-animal-plants-environment spheres are inseparable, so it is necessary to turn a directed look at the One Health approaches related to *N. fowleri.*

1. Introduction

Free-living amoebae (FLA) are protozoa widely distributed and have

conditions for their survival such as changes in temperature, pH and salinity (Khan, 2006; Schuster et al., 2004). One of the genera that have drawn attention for being more vulnerable to climate change and for

APÊNDICE III

Artigo intitulado “Metaproteomics as a tool to optimize the maize fermentation process” publicado em 03 de outubro de 2022, na revista Trends in Food Science & Technology. https://doi.org/10.1016/j.tifs.2022.09.017. O artigo é uma revisão critica da literatura que aborda sobre o potencial do uso da metaproteomica como um instrumento eficaz, mais econômico (tempo, recursos, mão de obra) para otimizar os processos fermentativos de grãos como o caso do milho.

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Metaproteomics as a tool to optimize the maize fermentation process

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ARTICLE INFO

Keywords:
Maize
Fermentation
Proteomics
Optimization
Processing
Conservation

ABSTRACT

Background: Maize dough is a fermentation product widely consumed in most African and Central American countries. Functional properties such as prebiotics, probiotics, and nutraceuticals of this dough have been widely documented.
However, it is still artisanal and seasonal, without quality assurance and brief shelf-life; the difficulties in processing and conservation force people to discontinue consumption. It is known that this dough forms an indispensable constituent in the daily life of the people in these countries.
Scope and approach: This review shows how metaproteomics data applied to studying the microbiota of fermented maize dough give better insights for optimizing the formulation process. And aim to help rescue and revaluate fermented maize dough in these people.
Key findings and conclusions: Omics are indeed indispensable tools and are increasingly being applied to fermented foods study. Using metaproteomic approaches became easier to make crucial decisions around the formulation, conservation, and shelf life of those products, offering results with a broad spectrum of applications in the fermentation process to optimize it.

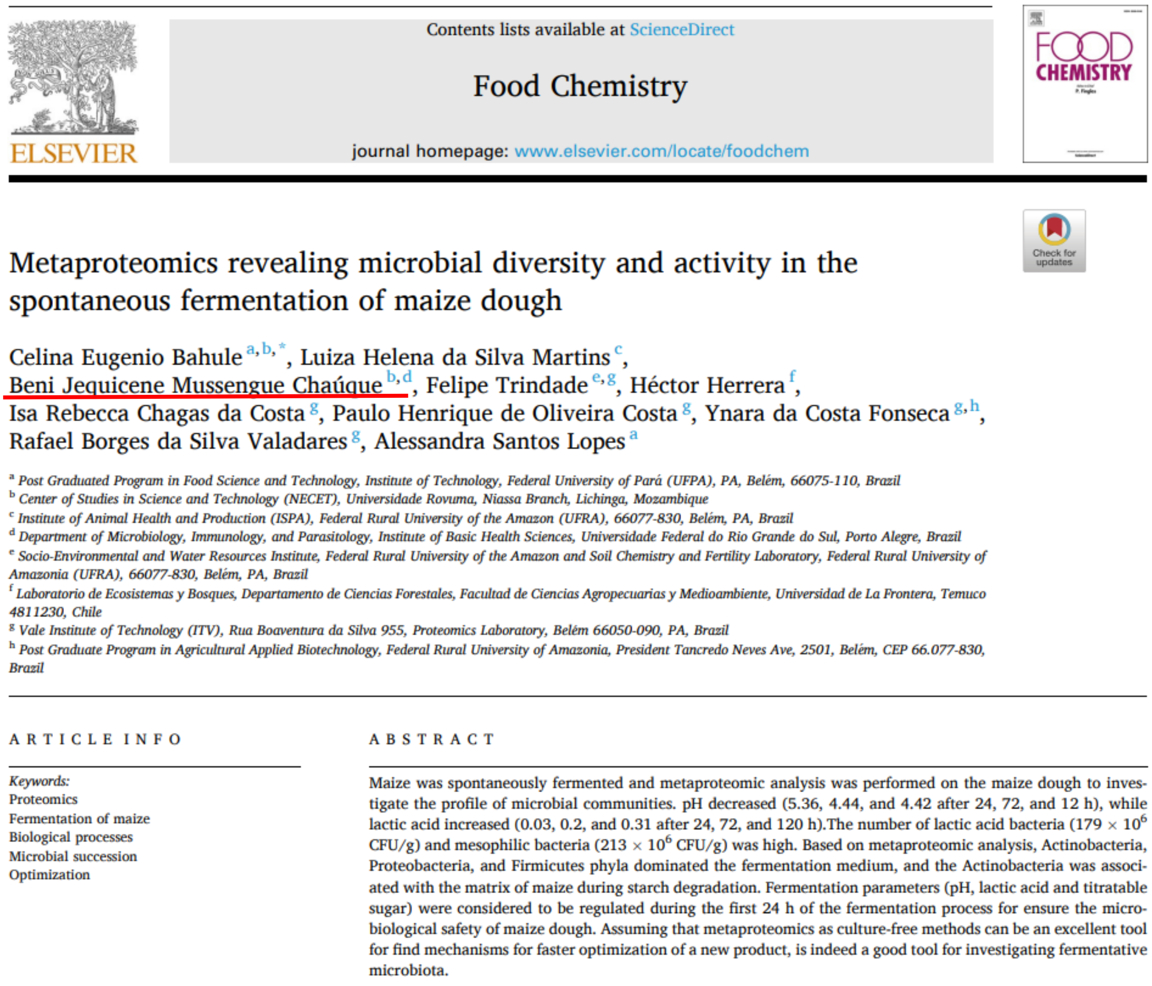
1. Introduction

Plant-based products are studied and launched on the market frequently, and fermented maize products with their associated functional properties have rich potential as an ingredient in this line. The termed clean label, plant-based, and have a consistent philosophy of little processing and with recognized and natural ingredients. In addition, they do lack any potentially harmful elements (Aschemann-Witzel et al., 2019a).

Although corn is the most produced crop globally, more than 80% of

APÊNDICE IV

Artigo intitulado "Metaproteomics revealing microbial diversity and activity in the spontaneous fermentation of maize dough" publicado em 13 de setembro de 2023 na revista Food Chemistry, https://doi.org/10.1016/j.foodchem.2023.137457. É um artigo original que utiliza a metaproteômica para caracterizar a dinâmica microbiana em processos fermentativos de milho. O artigo destaca ainda que a metaproteômica é uma técnica livre de cultura com melhor custo-benefício que permite identificar e caracterizar de forma detalhada os microrganismos e sua dinâmica.



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Food Chemistry

journal homepage: www.elsevier.com/locate/foodchem

Metaproteomics revealing microbial diversity and activity in the spontaneous fermentation of maize dough

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ARTICLE INFO

Keywords:
Proteomics
Fermentation of maize
Biological processes
Microbial succession
Optimization

ABSTRACT

Maize was spontaneously fermented and metaproteomic analysis was performed on the maize dough to investigate the profile of microbial communities. pH decreased (5.36, 4.44, and 4.42 after 24, 72, and 12 h), while lactic acid increased (0.03, 0.2, and 0.31 after 24, 72, and 120 h).The number of lactic acid bacteria (179 × 10^6 CFU/g) and mesophilic bacteria (213 × 10^6 CFU/g) was high. Based on metaproteomic analysis, Actinobacteria, Proteobacteria, and Firmicutes phyla dominated the fermentation medium, and the Actinobacteria was associated with the matrix of maize during starch degradation. Fermentation parameters (pH, lactic acid and titratable sugar) were considered to be regulated during the first 24 h of the fermentation process for ensure the microbiological safety of maize dough. Assuming that metaproteomics as culture-free methods can be an excellent tool for find mechanisms for faster optimization of a new product, is indeed a good tool for investigating fermentative microbiota.

APÊNDICE V

Artigo intitulado “Global prevalence of free-living amoebae in solid matrices – A systematic review with meta-analysis” publicado em 25 de agosto de 2023 na revista Acta Tropica, https://doi.org/10.1016/j.foodchem.2023.137457. É um artigo de revisão sistemática com metanálise que relata a prevalência de global de amebas de vida livre em diferentes matrizes solidas ambientais (solo, sedimento, poeira, lodo, filtros, etc).

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Global prevalence of free-living amoebae in solid matrices – A systematic review with meta-analysis

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ARTICLE INFO

Keywords:
Soil
Dust
Sediment
Mud
Sludge
Compost
Acanthamoeba
Balamuthia

ABSTRACT

The ubiquitous free-living amoebae (FLA) are microorganisms of significant medical, sanitary, and ecological importance. However, their characterization within solid matrices such as soil, dust, sediment, mud, sludge, and compost remain to be systematized. In this study, we conducted a systematic review with meta-analysis to explore the global distribution of FLA in solid matrices. From the analysis of 104 out of 4,414 scientific articles retrieved from different databases, it was found that the general global prevalence of FLA in solid matrices was of 55.13% (95% confidence interval (CI) 49.32–60.94). Specifically, FLA prevalence was high in soil (72.40%, 95% CI 69.08–75.73), sediment (57.91%, 95% CI 50.01–65.81), mud (52.90%, 95% CI 24.01–81.78), dust (48.60%, 95% CI 43.00–54.19), and sewage sludge (40.19%, 95% CI 30.68–49.70). In aerosols it was comparatively lower

APÊNDICE VI

Artigo intitulado “Imidazolium ionic liquid as potential contact lens disinfectant inactivating cystic resistance forms from Acanthamoeba keratitis” publicado em 20 de outubro de 2023 na revista Journal of Tropical Pathology. https://doi.org/10.5216/rpt.v52i3.76409. É um artigo original que relata a potente atividade cisticida dos líquidos iônicos de imidazol, destacando o potencial do seu uso como desinfetante de superfícies e de lentes de contato.

ORIGINAL ARTICLE

IMIDAZOLIUM IONIC LIQUID AS POTENTIAL CONTACT LENS DISINFECTANT INACTIVATING CYSTIC RESISTANCE FORMS FROM *Acanthamoeba* KERATITIS

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ABSTRACT

Keratitis caused by *Acanthamoeba* spp. is a rare disease, although increasingly common, especially among contact lens users. The occurrence and the devastating effect of this disease are associated with the lack of care in cleaning and disinfecting lenses and their storage cases, as well as ineffective drugs to mainly eliminate the parasite’s cysts. This work evaluated the amoebicidal activity of the imidazolium salt 1-hexadecyl-3-methylimidazolium chloride ($C_{16}MImCl$) against cysts of two characterized isolates from *Acanthamoeba* keratitis cases (MZ404337 and MZ404332). The inactivation of 100% of the cysts was achieved at a concentration of 7.81 µg/mL for MZ404337 and of 1.95 µg/mL for MZ404332, both at 24

APÊNDICE VII

Manuscrito intitulado “Agar dehydration: A simple method for long-term storage of *Acanthamoeba* spp. collection at room temperature” aceito para publicação na Revista Parasitology Research”. É um artigo original que descreve o desenvolvimento de um método alternativo e barato de transpote e para conservação a longo prazo de cepas de Acanthamoeba.

Agar dehydration: A Simple Method for Long-Term Storage of *Acanthamoeba* spp. Collection at Room Temperature

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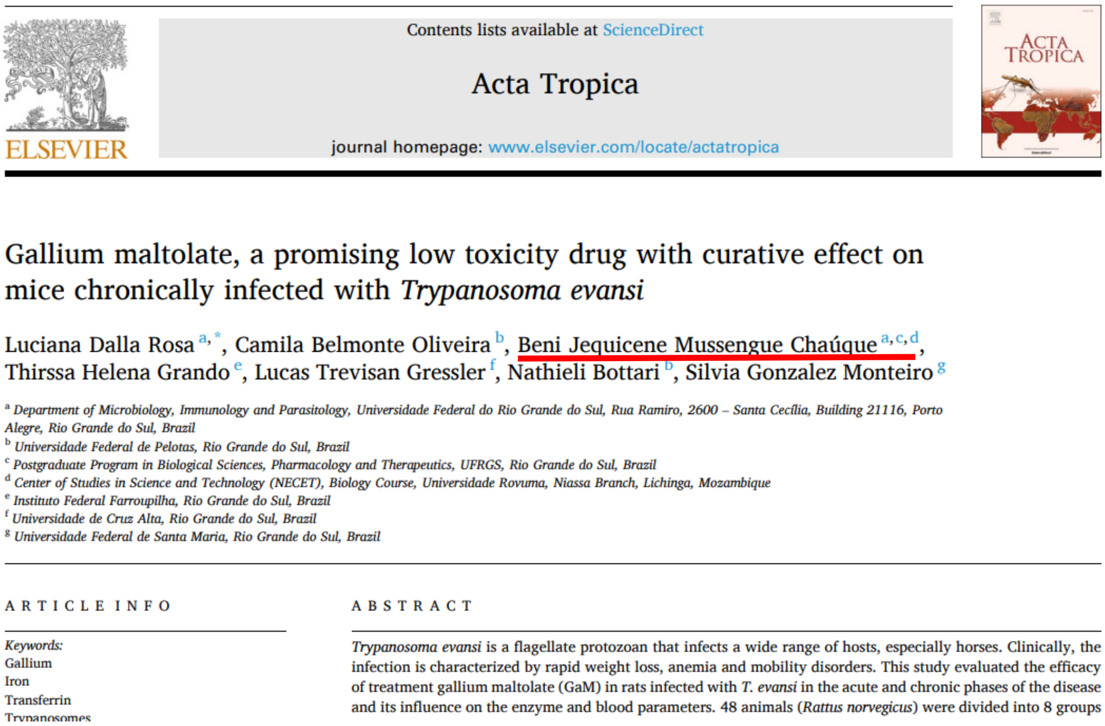
Abstract

This study describes dehydration of agar containing cysts as a novel and inexpensive method of long-term storage of *Acanthamoeba* spp. collections at room temperature. 500 µl of axenically cultured *Acanthamoeba* spp. trophozoites (10^6 cells/mL) in PYG media were spread on the surface of sterile non-nutritive agar (NNA, 2-3 mm thick). Similarly, 150 µl of the amoeba suspension (10^6 cells or cysts/mL) from monoxenic plate culture was added to NNA with a layer of heat-inactivated *Escherichia coli*. The plates were incubated at 30°C and after encystment the parafilm® was removed and the plates were kept at the same temperature until the NNA was completely dehydrated. The dehydrated cysts-containing NNA was cut into rectangles and stored in airtight tubes at room temperature for up to 3 years. Cyst viability was assessed by inoculating them in fresh NNA with a layer of *E. coli* and in PYG followed by incubation at 30°C. 100% of samples from all specimens (19) stored over the three years allowed new cultures to be re-established, except two strains showed reduced reculturability, at 66.7% and 62.5%, after two years of room temperature storage. 100% of the cyst samples produced axenically and maintained in dry NNA allowed the reestablishment of axenic cultures through direct incubation in PYG, with excystment occurring within 24 or 48 hours. For the first time, we report the dehydration of cyst-containing agar as an economical and effective method for the long-term storage of *Acanthamoeba* spp. collections at room temperature. It enables the creation of large collections and cost-effective transport of *Acanthamoeba* strains.

Keywords: *Acanthamoeba* spp., collection storage, culturability, cysts, preservation.

APÊNDICE VIII

Manuscrito intitulado “A Gallium maltolate, a promising low toxicity drug with curative effect on mice chronically infected with *Trypanosoma evansi*”. publicado em 12 de fevereiro de 2024 na revista Acta Tropica. http://dx.doi.org/10.1016/j.actatropica.2024.107148. É um artigo original que descreve a avaliação do efeito tripanocida do maltolato em modelos agudo e crônico invivo de tripanossomíase.



Contents lists available at ScienceDirect

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journal homepage: www.elsevier.com/locate/actatropica

Gallium maltolate, a promising low toxicity drug with curative effect on mice chronically infected with *Trypanosoma evansi*

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ARTICLE INFO

Keywords:
Gallium
Iron
Transferrin
Trypanosomes

ABSTRACT

Trypanosoma evansi is a flagellate protozoan that infects a wide range of hosts, especially horses. Clinically, the infection is characterized by rapid weight loss, anemia and mobility disorders. This study evaluated the efficacy of treatment gallium maltolate (GaM) in rats infected with *T. evansi* in the acute and chronic phases of the disease and its influence on the enzyme and blood parameters. 48 animals (*Rattus norvegicus*) were divided into 8 groups

APÊNDICE IX

Manuscrito intitulado “Global prevalence of potentially pathogenic free-living amoebae in sewage and sewage-related environments – Systematic review with meta-analysis”. No prelo, na Revista Parasitology Research, https://doi.org/10.1007/s00436-024-08164-7. É uma revisão sistemática com metanálise, que objetivou caracterizar a prevalencia de amebas de visa livre no esgoto e ambientes contaminados por esgoto.

Global prevalence of potentially pathogenic free-living amoebae in sewage and sewage-related environments – Systematic review with meta-analysis

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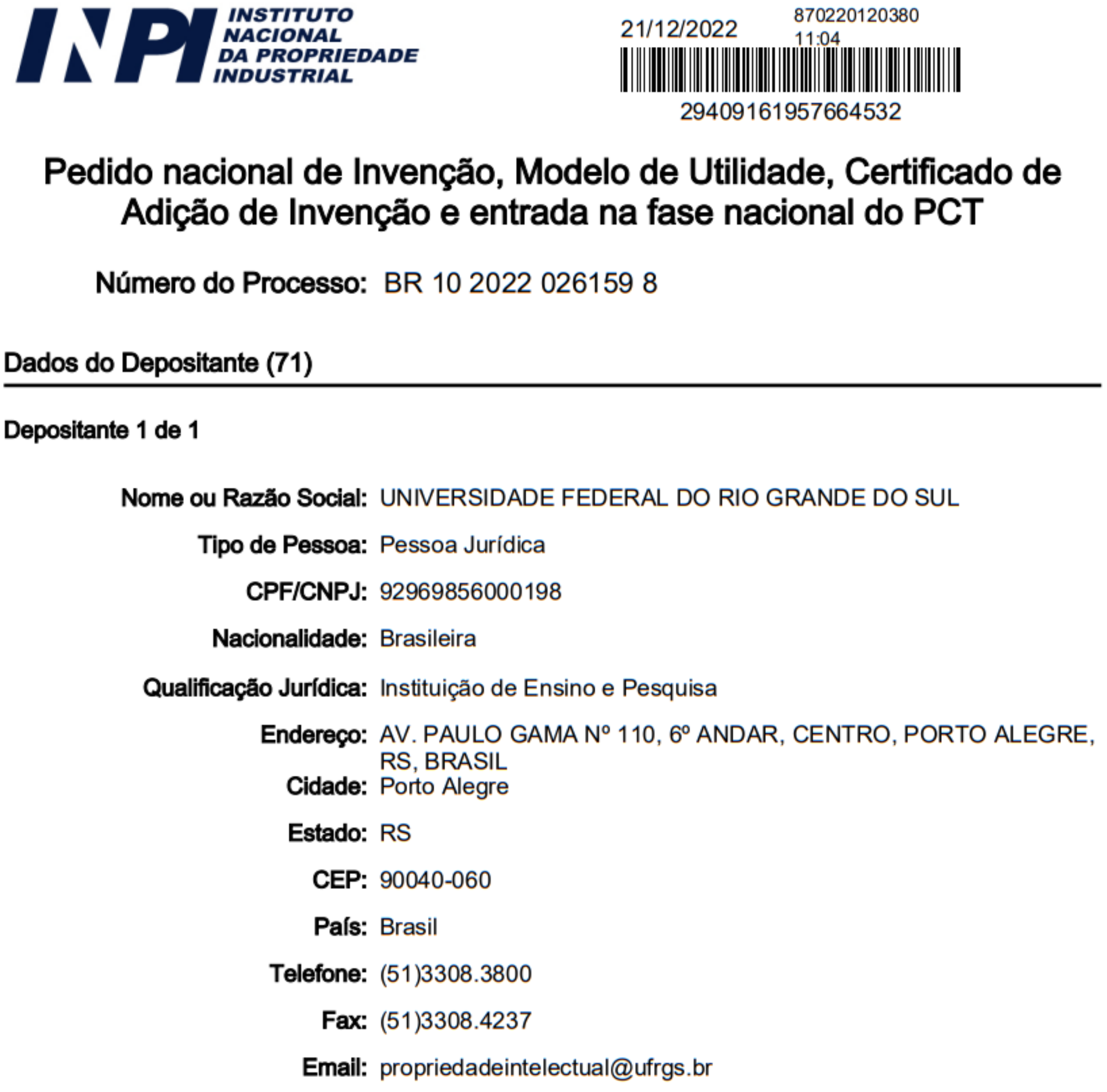
ABSTRACT

Free-living amoebae (FLA) include amphizoic microorganisms important to public health, widely isolated from air, water and soil. However, its occurrence in sewage-related environments still needs to be systematically documented. This study synthesize the occurrence of FLA in sewage-related environments through a systematic review with meta-analysis. A total of 1983 scientific articles were retrieved from different databases, of which 35 were selected and analyzed using a random effects forest plot model with a 95% confidence interval (IC). The pooled overall prevalence of FLA in sewage across 12 countries was 68.96% (95% IC = 58.5–79.42). Subgroup analysis indicates high prevalence in all environments analyzed, including sewage water from the sewage treatment plant (81.19%), treated sewage water (75.57%), sewage-contaminated water (67.70%), sediment contaminated by sewage (48.91%) and sewage water (47.84%). Prevalence values of *Acanthamoeba* spp., *Hartmanella*/*Vermamoeba* spp., and *Naegleria* spp. are 47.48%, 28.24% and 16.69%, respectively. Analyzing the species level, the distribution is as follows: *Acanthamoeba palestinensis* (88%), *A. castellanii* (23.74%), *A. astronyxis* (19.18%), *A. polyphaga* (13.59%), *A. culbertsoni* (12.5%), *A. stevenson* (8.33%), *A. tubiashi* (4.35%) and *A. hatchetti* (1.1%), *Naegleria fowleri* (28.4%), N. gruberi (25%), *N. clarki* (8.33%), *N. australiensis* (4.89%) and *N. italica* (4.29%), *Hartmannella/Vermamoeba exundans* (40%) and *H.V. vermiform* (32.61%). Overall, our findings indicate a high risk associated with sewage-related environments, as the prevalence of FLA, including pathogenic strains, is high, even in treated sewage water. The findings of this study may be valuable both for risk remediation actions against amoebic infections and for future research endeavors.

Keywords: *Acanthamoeba*, *Vermamoeba*/*Hartmannella*, *Naegleria*, sewage water, treated sewage water, sewage-contaminated sediment / water.

APÊNDICE X

Pedido de depósito de patente intitulado “Sistema Multiplicador da Área de Coleta de Radiação Solar e Processos de Tratamento de Fluidos” depositado no Instituto Nacional de Propriedade Industrial (INPI) sob o número BR 102022026159-8.



INPI INSTITUTO NACIONAL DA PROPRIEDADE INDUSTRIAL

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Pedido nacional de Invenção, Modelo de Utilidade, Certificado de Adição de Invenção e entrada na fase nacional do PCT

Número do Processo: BR 10 2022 026159 8

Dados do Depositante (71)

Depositante 1 de 1

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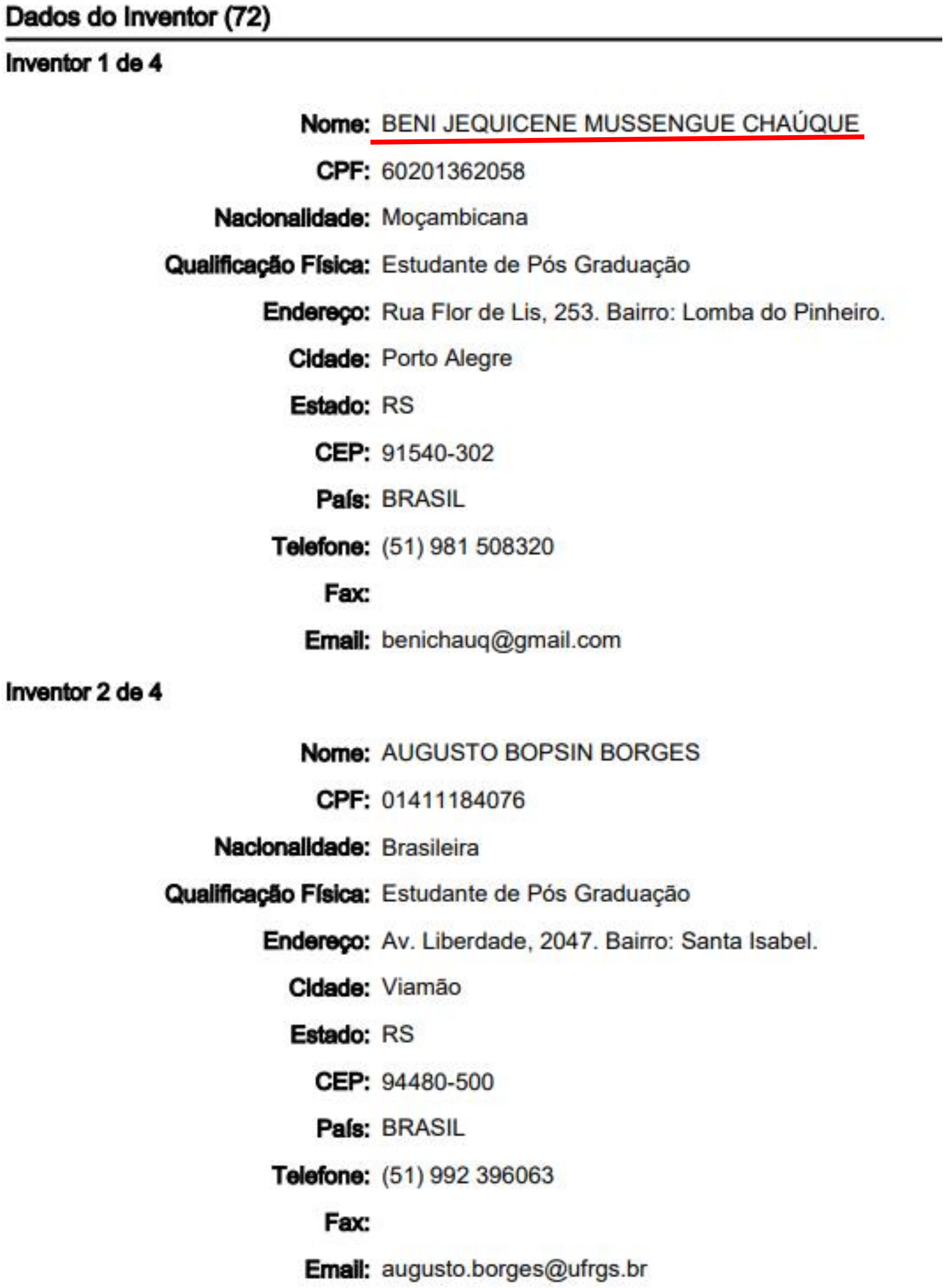
Dados do Pedido

Natureza Patente: 10 - Patente de Invenção (PI)

Título da Invenção ou Modelo de Utilidade (54): Sistema multiplicador da área de coleta de radiação solar e processos de tratamento de fluidos

Resumo: A invenção trata de um sistema multiplicador de área de radiação solar e processos de tratamento de fluidos em dispositivos solares. A inovação compreende um sistema de coleta e concentração de radiação, com capacidade de rastrear o sol, e que acopla dispositivos que utilizam a energia solar para processar fluidos por meio de aquecimento e descontaminação microbiológica e química mediada pelo calor e radiação UV, em processos de alta produtividade. A presente inovação se enquadra no campo técnico da engenharia ambiental, engenharia de processos, saneamento, e é aplicável no campo de aquecimento solar de fluidos, processamento térmico de alimentos, descontaminação biológica e química de águas residuais, bem como na desinfecção de água potável.

Figura a publicar: 1



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Relatório Descritivo de Patente de Invenção

SISTEMA MULTIPLICADOR DA ÁREA DE COLETA DE RADIAÇÃO SOLAR E PROCESSOS DE TRATAMENTO DE FLUIDOS

Campo da Invenção

[001] A presente inovação descreve uma solução que multiplica por várias dezenas de vezes a área de coleta de radiação de dispositivos que utilizam a energia solar para processamento de fluidos, por meio de um sistema de coleta e concentração de radiação solar, capaz de rastrear o sol, e com isso coletar, disponibilizar e utilizar grandes quantidades de energia, o que resulta em alta produtividade de fluidos processados. Esta inovação se enquadra no campo técnico da engenharia ambiental, engenharia de processos, saneamento, energia, e é aplicável no campo de aquecimento solar de fluidos, processamento térmico de alimentos, descontaminação biológica e química de águas residuais, bem como na desinfecção de água potável.

Antecedentes da Invenção

[002] As tecnologias de aquecimento de fluidos são necessárias em diferentes atividades humanas, e são empregadas em atividades domésticas bem como industriais. Sendo uma necessidade social perene, tecnologias sustentáveis e de baixo custo capazes de suprir a demanda existente são altamente desejáveis. Tecnologias baseadas na radiação solar, como os aquecedores solares são soluções emergentes de alto potencial. Apesar dos aquecedores solares serem cada vez mais utilizados eles possuem uma importante limitação que tem implicação na sua produtividade e custo, especificamente, a pequena área de coleta de radiação solar. Esta limitação resulta diretamente em baixa produtividade de fluidos processados por unidade, aquecimento lento ou temperaturas abaixo do ideal, principalmente em dias pouco ensolarados. Atualmente, o aumento da área de coleta implica inevitavelmente na aquisição

FIGURAS

Figura 1

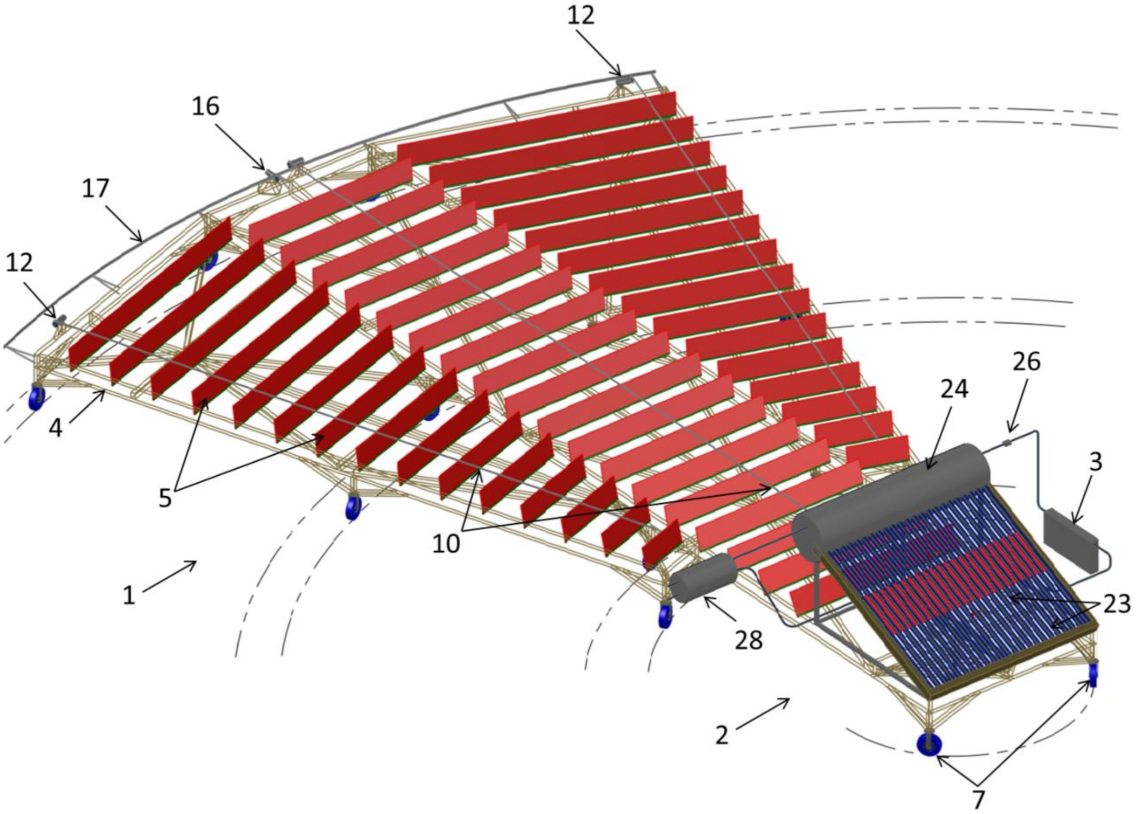
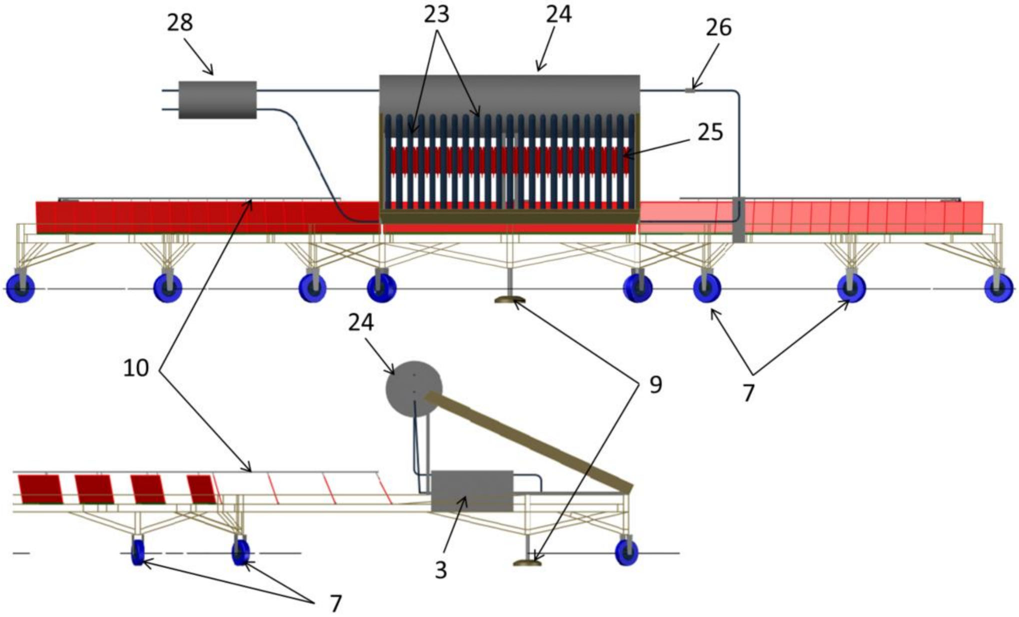


Figura 2



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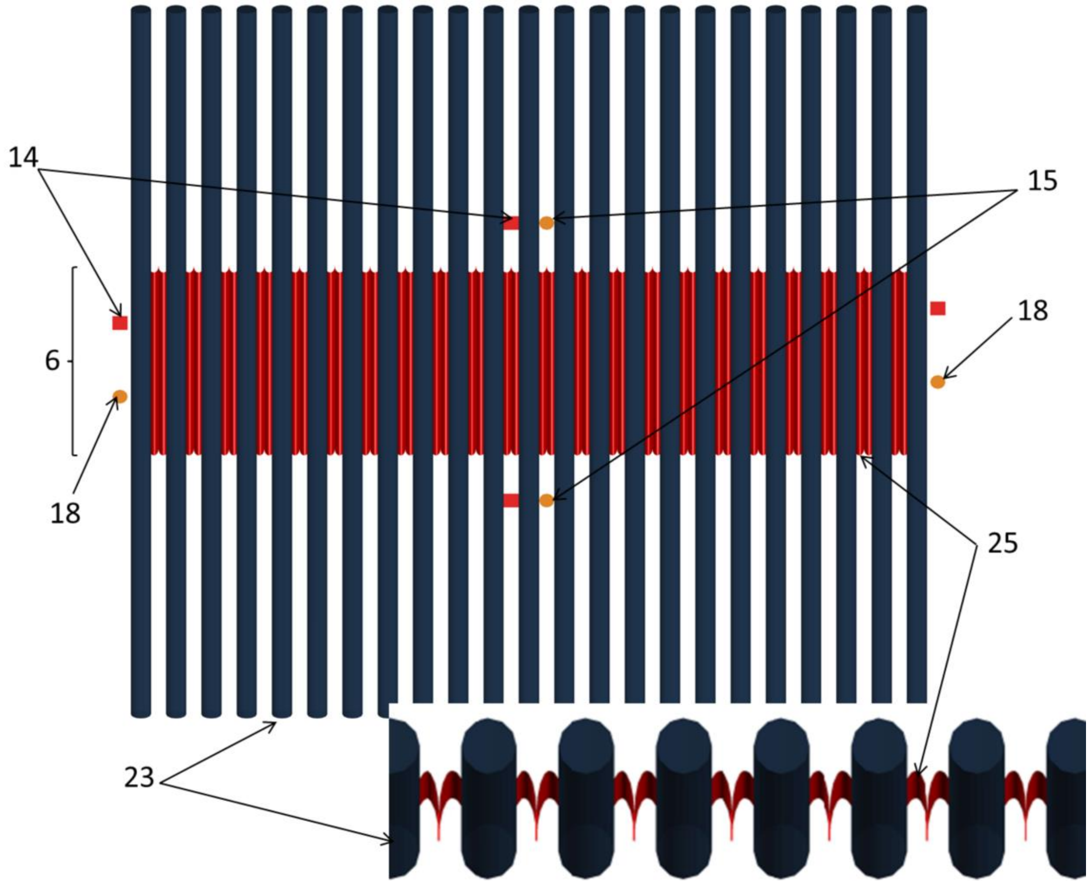

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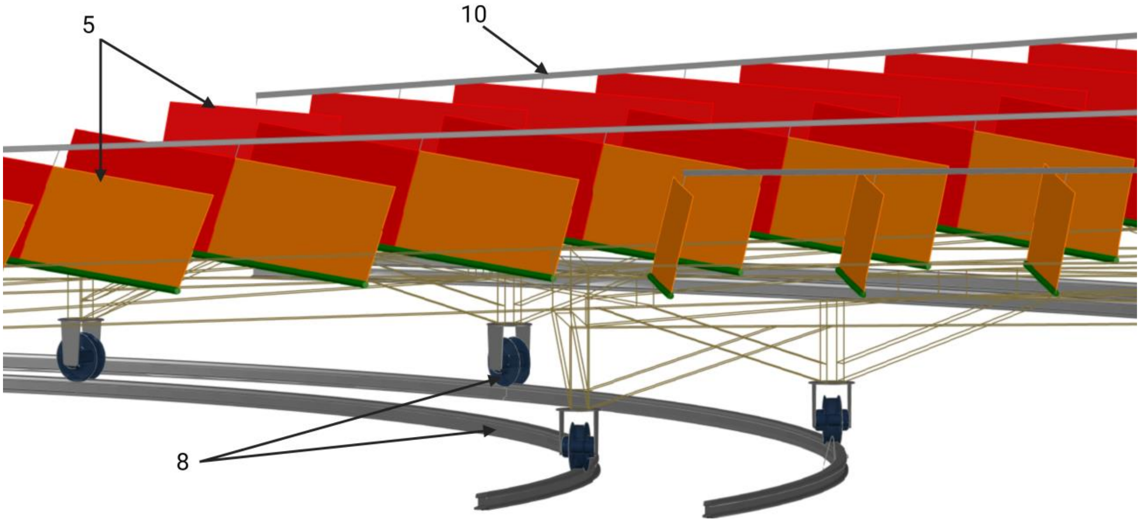

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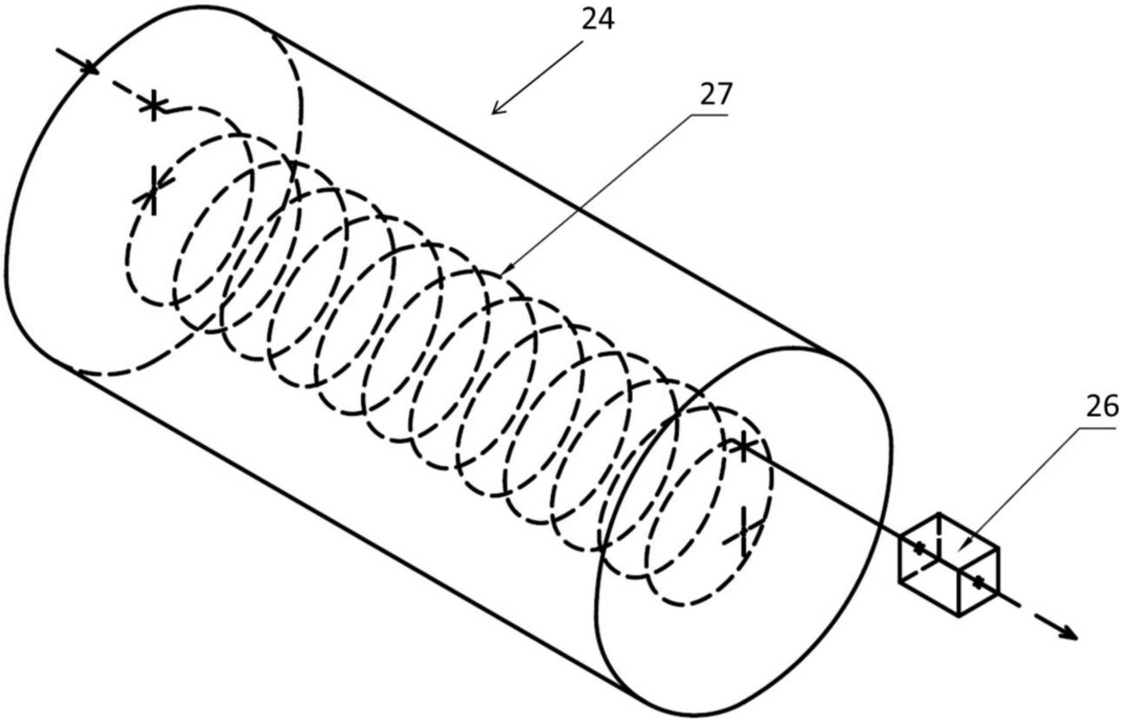

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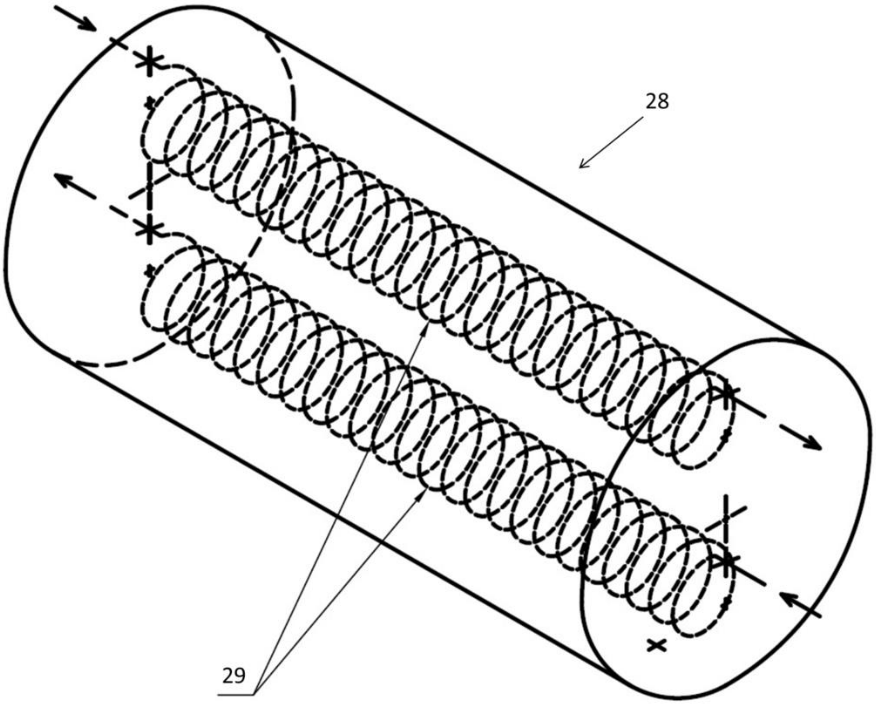

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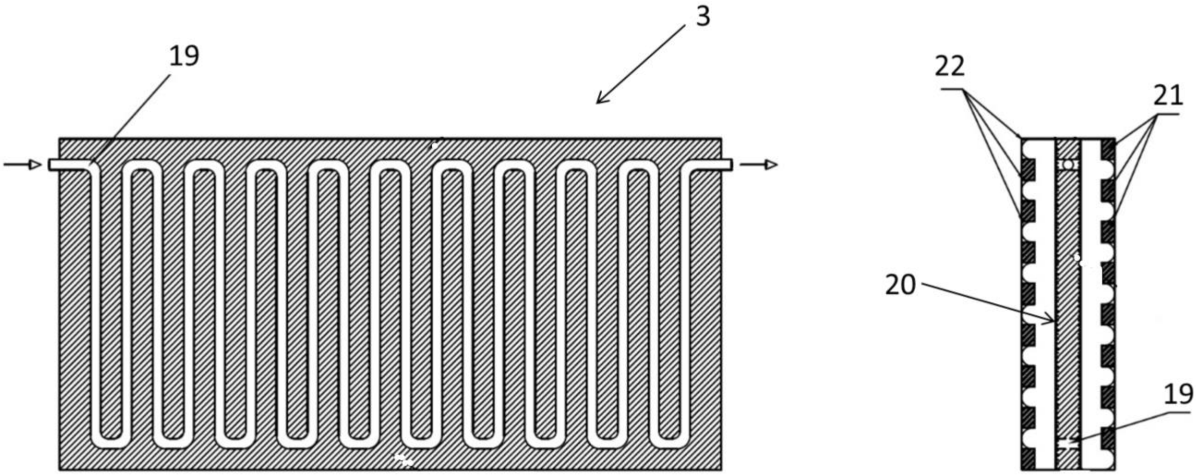

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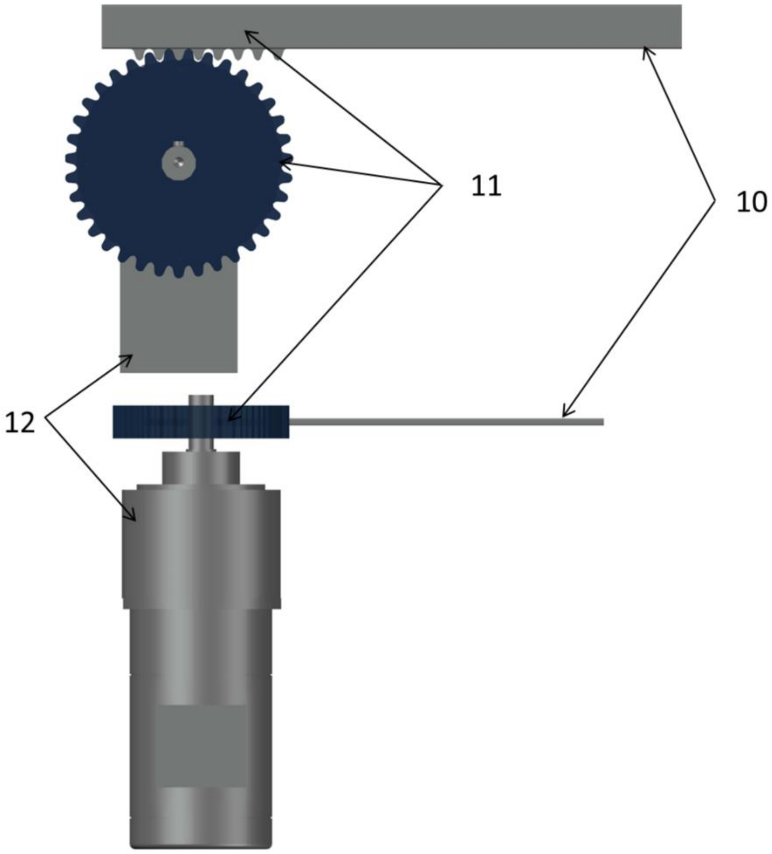

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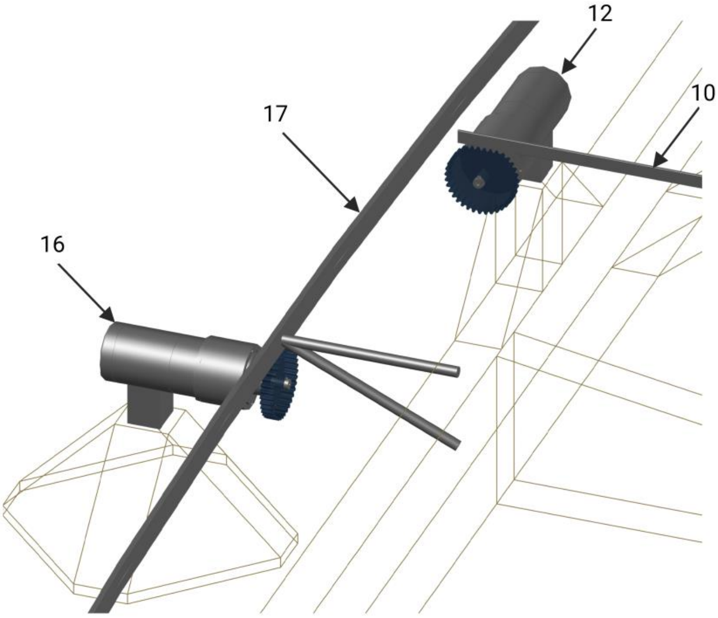


Figura 10

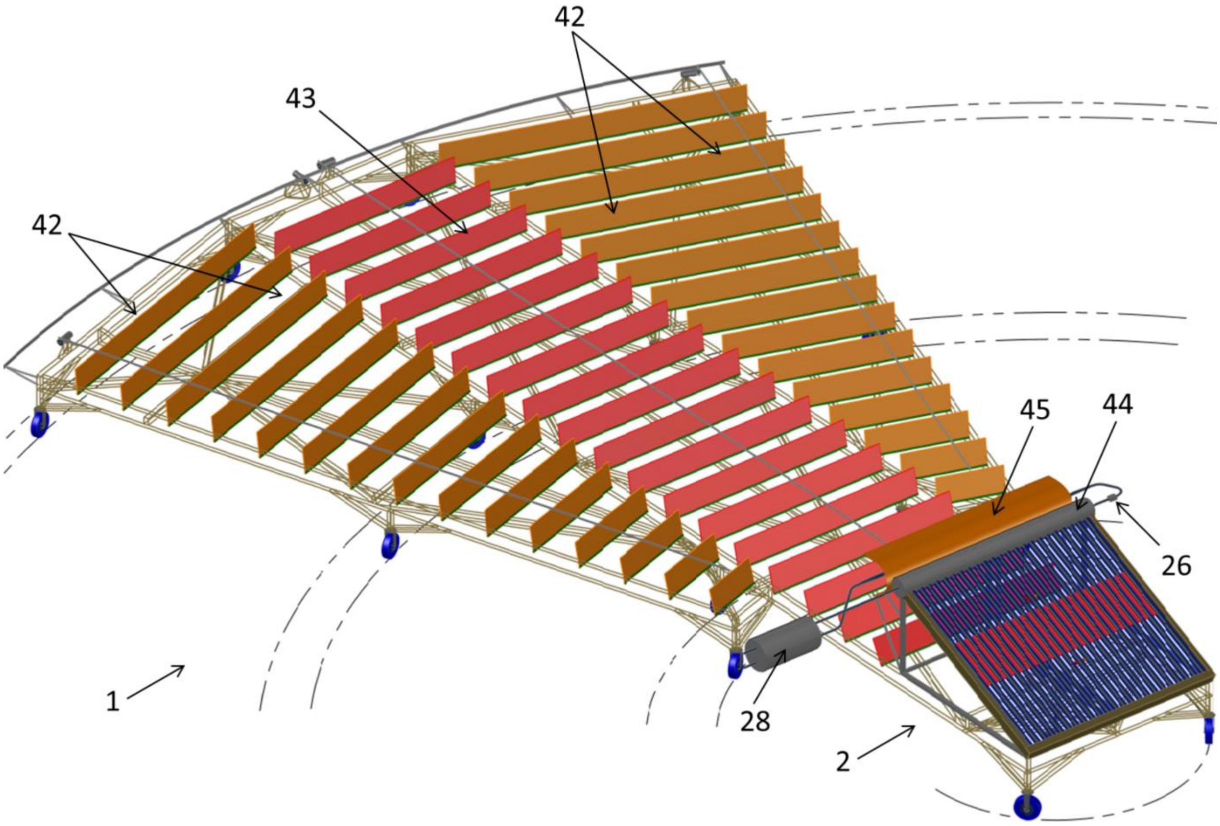


Figura 11

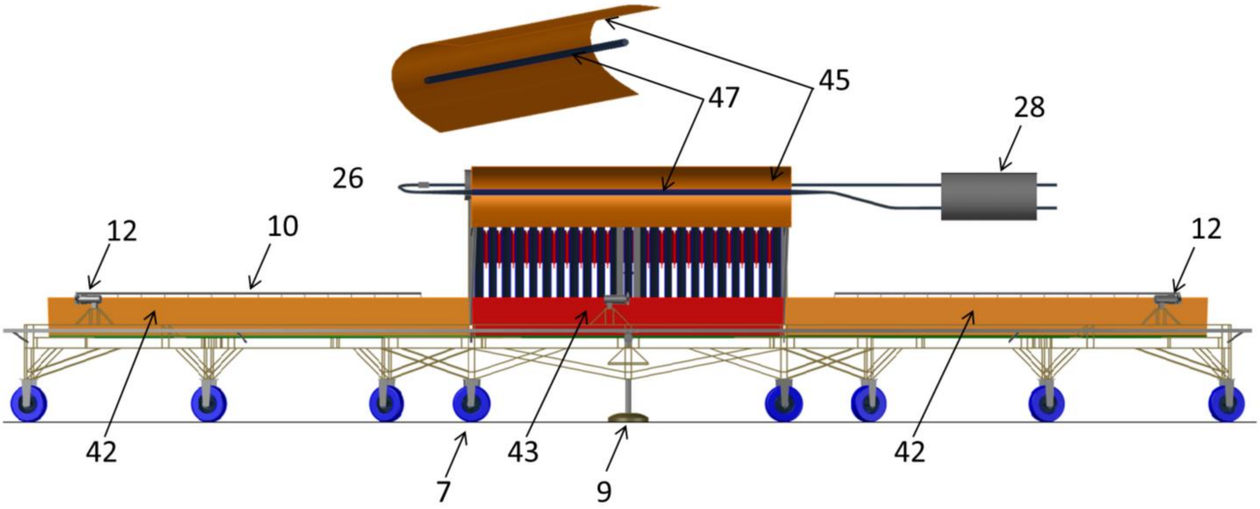


Figura 12

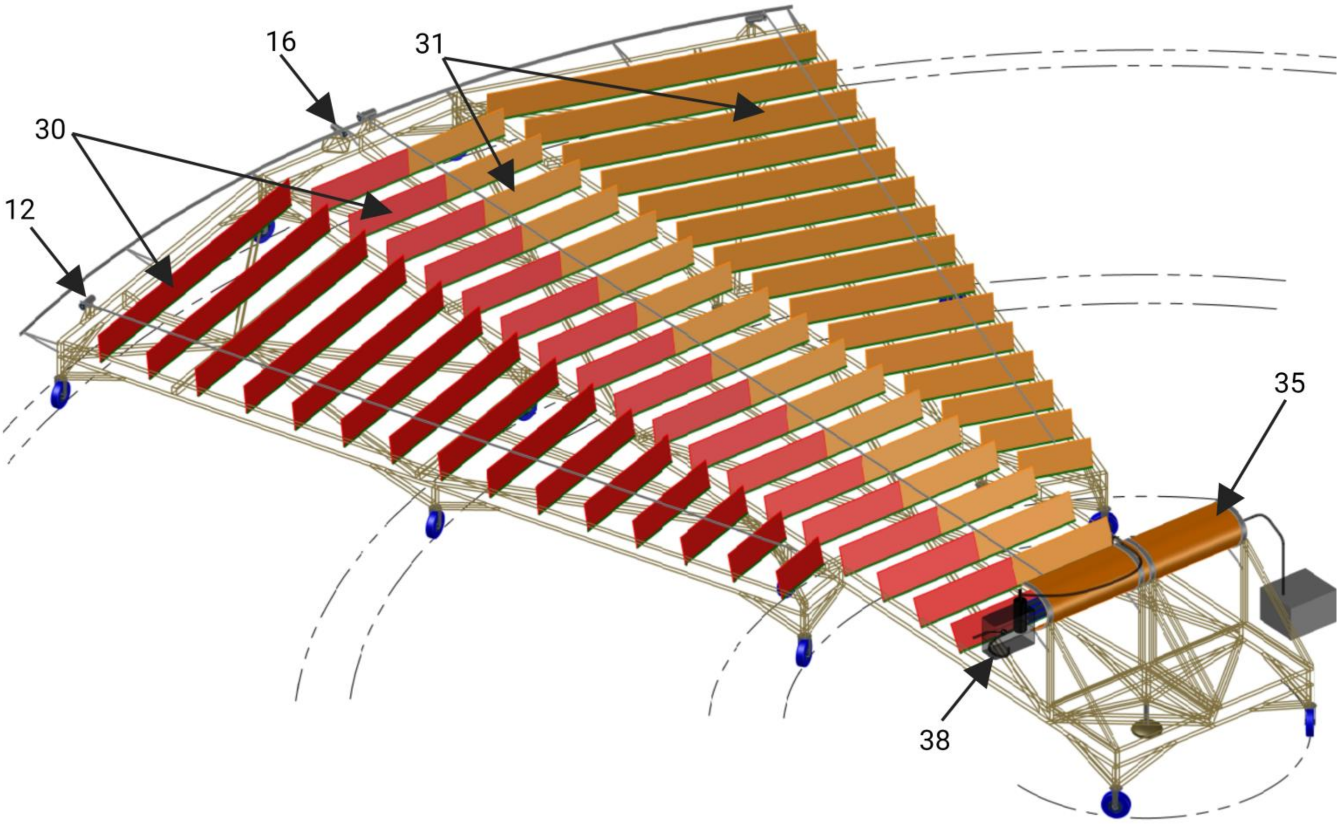
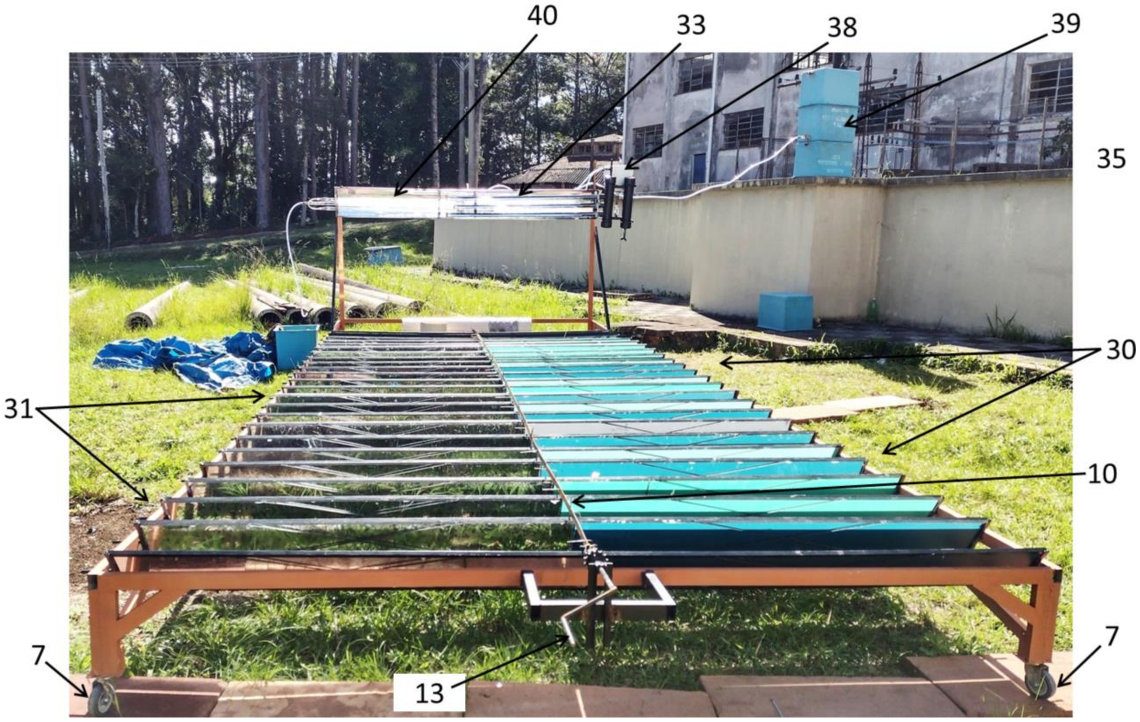


Figura 13



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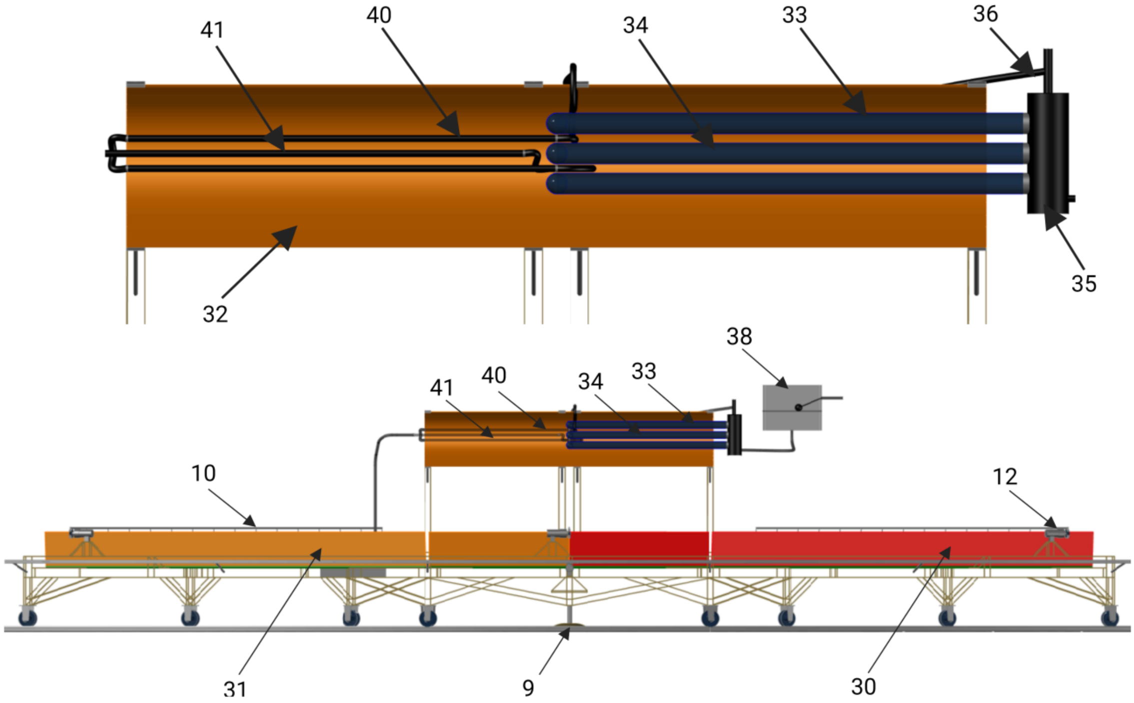


Figura 15

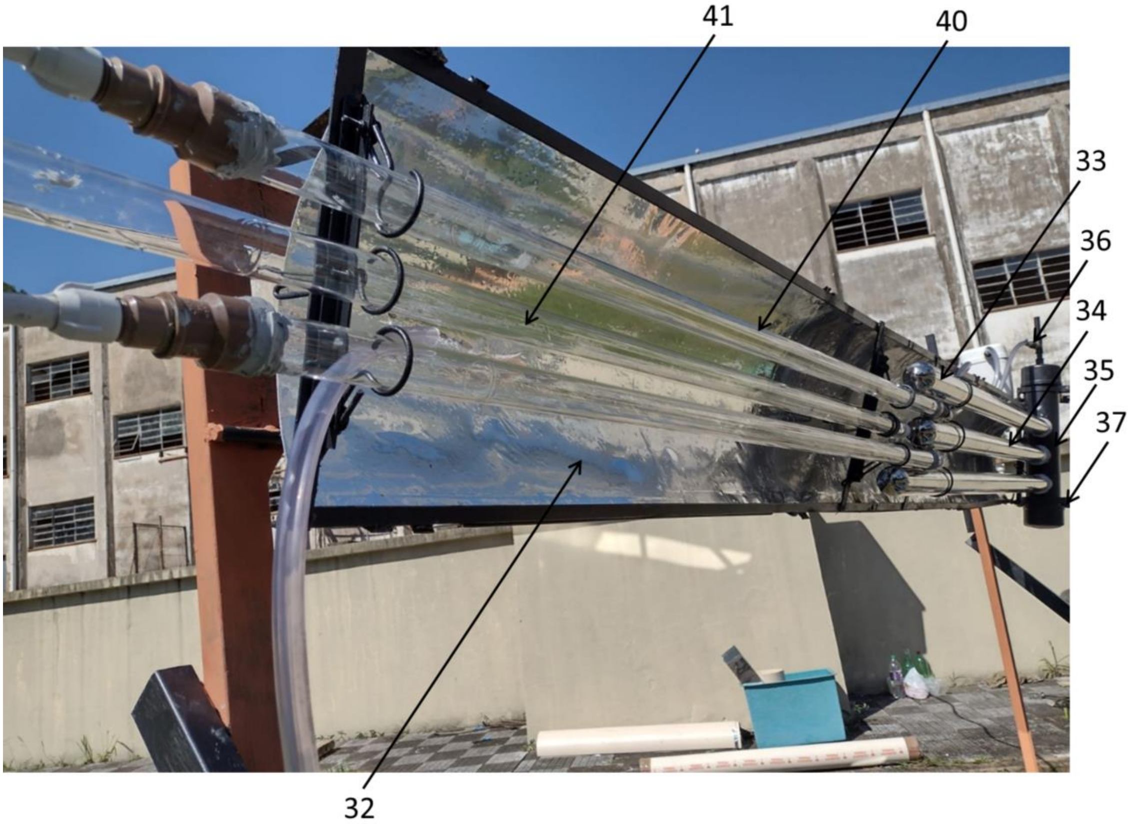
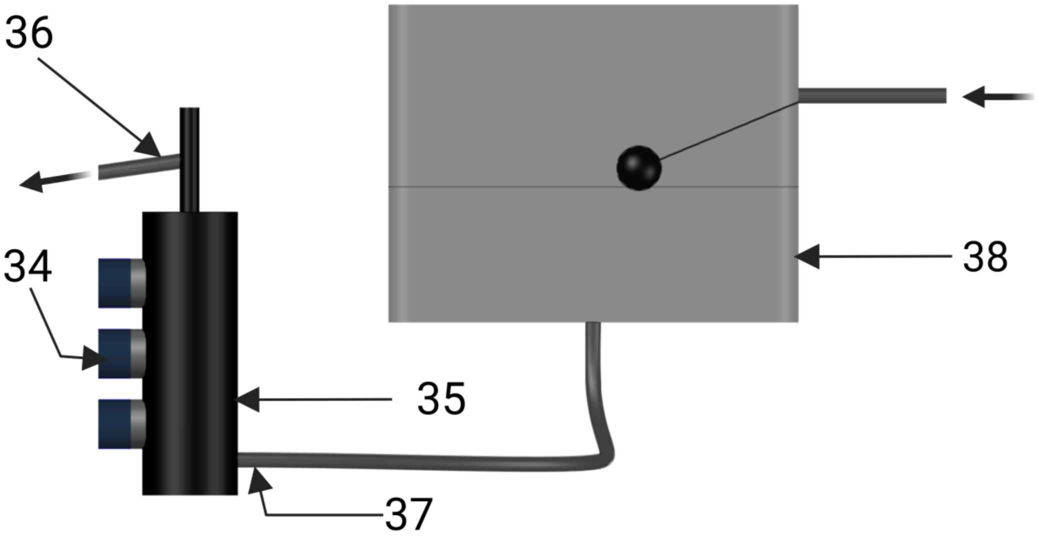


Figura 15



APÊNDICE XI

Supplementary material

Development of solar water disinfection systems for large-scale public supply, state of the art, improvements and paths to the future - A systematic review

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LITERATURE RETRIEVAL STRATEGY

Retrieving scientific papers

The scientific articles included in this review were retrieved through searches carried out in three databases, namely, Science Direct, Web of Science and Scopus, using the following keywords or a combination of them: “Solar water disinfection AND systems” OR “Solar Pasteurization AND Systems” OR “SODIS systems” OR “SOPAS systems” OR “Solar water treatment AND devices”. Searches were carried out between August 10 and 18, 2021. Original articles and reviews of the scientific literature, written in English, published in the last two decades (between 2000 - 2021) were included. The references of the selected articles were also accessed to search for some interesting literature.

Inclusion criteria

Articles dealing with the development of solar water disinfection systems, which have the potential to be used or improved for the development of high-performance solar disinfection systems, applicable in large-scale and low-cost drinking water supply, were selected. Only articles that present a clear description of the configurations of the developed systems were included.

Articles dealing with systems based on photocatalytic, photothermal methods or using other energy sources (not solar energy) were not included, except for those that describe systems with innovative configuration and contribute to the advancement of the state of the art in the development of solar disinfection systems that produce large volumes of drinking water at low cost.

Retrieving patents

This review also includes information obtained from patents. The patents were retrieved through searches carried out in the international database of patent families “Fampat”, between the 15th and 30th of October, 2021, using the Orbit tool from Questel ©, in the “Essential” service level. The universe of patents of interest was accessed through the following search terms: (C02F-001/32 OR C02F-001/30 OR C02F-001/16 OR C02F-001/14 OR C02F-001/10 OR C02F-001/02 OR C02F-009/10 OR C02F-2201/009 OR C02F-2201/32 OR C02F-2201/3228 OR Y02A-20/208 OR Y02A-20/211 OR Y02A-20/142 OR F24S-010/00 OR F24S-020/00 OR F24S-021/00 OR F24S-023/00 OR F24S-025/00 OR F24S-030/00)/IPC/CPC. Each of the search terms corresponds to a particular section, class, subclass and group or subgroup that bring together the patents of interest for this study according to the criteria of the "International Patent Classification (IPC)" and "Patent Classification Cooperatives (CPC)”. Details on the meaning of each of the search terms used are presented in the supplementary material (Table S2). The screening for the selection of search terms was carried out by consulting the ESPACENET website (https://worldwide.espacenet.com/patent/cpc-browser) and from the IPCPUB website, Version 8.5 (http://ipc.inpi.gov.br/classifications/ipc/ipcpub). During queries, the following subclasses were highlighted: C02F “Treatment of water, Waste water, Sewage, OR Sludge”; Y02A “Technologies for adaptation to climate change” e F24S “Solar heat collectors; Solar heat systems”. Only patents filed between 2006 and 2021 were considered. In this phase, a universe of 65,662 patents was recovered.

From the universe of patents retrieved in step A (Table S1), only patents that present in their titles and/or claims, the following filtering keywords were selected: ((SOLAR OR SUNLIGHT OR SUN OR HELIOTHERMAL) AND (((WATER 10W (TREATMEN+ OR DISINFECTION+ OR DECONTAMINA+ OR PURIFICAT+ OR PASTEURIZAT+ OR STERILIZAT+ OR HEAT+)) OR ((MIRROR OR MIRRORS OR REFLECT+) OR (HEAT W COLLECTOR+) OR REATOR+ OR REACTOR)))). Screening in this step B resulted in the selection of 7,011 patents.

The patents selected in step B were submitted to a screening. In this step C (Table S1), all patents that contained the following keywords in their titles and/or claims were discarded. (SALIN+ OR SAL OR SEAWATER OR SEA OR VAPOR+ OR EVAPO+ OR STEEM OR DESALIN+ OR DISTILL+ OR DISTILLER+ OR CONDENSAT+ OR ALGA+ OR COMPRESSOR OR MAGNETIC+ OR PHOTOCATALYSIS OR PHOTOLYSIS OR LASER OR LED OR OZONE OR OZONISATION OR OXYGENATION OR ELECTRODE OR CATALYTIC OR CHLORIN+ OR CHEMICA+ OR ALKALINE OR

BIOELECTROCHEMICAL OR NANO+ OR HYDROGEN OR (PHOTOTHERMAL W NANOMATERIAL) OR DIOXIDE OR TITANIUM OR TIO2 OR DYE OR (CARBON W FIBER) OR OSMOSIS OR FILTE+ OR FILTRA+ OR EXCREMENT OR STOOL OR SEWAGE OR SLUDGE OR BULLFROG OR POOL OR FLOATING OR FUEL OR GASOLINE OR OIL). This set of keywords that make up the exclusion criteria was accessed by reading the titles and abstracts of the patents selected in step B. Words that did not correspond to the objective of the searches and that represented documents far from the innovations targeted by this review were selected. At this stage, 1938 patents were selected. These patents were submitted to screening, which consisted of reading the title, abstract, claims and image analysis, and the selected patents were read in full, as described in Figure 2. Patents written in English and reporting innovations that can be used in the development or improvement of high-performance solar water treatment systems were selected. Patents whose innovations are not exhaustively described in scientific articles were preferably included in the review.

Table S1. Summary of patent search and screening steps

Stage	**Search terms**	**Field**	**Retrieved patents**	**Description**
A	(C02F-001/32 OR C02F-001/30 OR C02F-001/16 OR C02F-001/14 OR C02F-001/10 OR C02F-001/02 OR C02F-009/10 OR C02F-2201/009 OR C02F-2201/32 OR C02F-2201/3228 OR Y02A-20/208 OR Y02A-20/211 OR Y02A-20/142 OR F24S-010/00 OR F24S-020/00 OR F24S-021/00 OR F24S-023/00 OR F24S-025/00 OR F24S-030/00)/IPC/CPC	IPC/CPC	65.662	(A) - Search was performed by International Patent Classification (IPC), Cooperative Patent Classification (CPC) and filtering by time range. Only documents filed between 2006 and 2021 were considered.
B Inclusion criteria	A AND ((SOLAR OR SUNLIGHT OR SUN OR HELIOTHERMAL) AND (((WATER 10W (TREATMEN+ OR DISINFECTION+ OR DECONTAMINA+ OR PURIFICAT+ OR PASTEURIZAT+ OR	TI/CLMS	7.011	(A-B) - Do From the universe of patents resulting from step (A), only the

	STERILIZAT+ OR HEAT+)) OR ((MIRROR OR MIRRORS OR REFLECT+) OR (HEAT W COLLECTOR+) OR REATOR+ OR REACTOR))))/TI/CLMS			documents that presented the words listed in the search terms of step (B) in the title and/or in their claims were selected.
C Exclusion criteria	B AND (SALIN+ OR SAL OR SEAWATER OR SEA OR VAPOR+ OR EVAPO+ OR STEEM OR DESALIN+ OR DISTILL+ OR DISTILLER+ OR CONDENSAT+ OR ALGA+ OR COMPRESSOR OR MAGNETIC+ OR PHOTOCATALYSIS OR PHOTOLYSIS OR LASER OR LED OR OZONE OR OZONISATION OR OXYGENATION OR ELECTRODE OR CATALYTIC OR CHLORIN+ OR CHEMICA+ OR ALKALINE OR BIOELECTROCHEMICAL OR NANO+ OR HYDROGEN OR (PHOTOTHERMAL W NANOMATERIAL) OR DIOXIDE OR TITANIUM OR TIO2 OR DYE OR (CARBON W FIBER) OR OSMOSIS OR FILTE+ OR FILTRA+ OR EXCREMENT OR STOOL OR SEWAGE OR SLUDGE OR BULLFROG OR POOL OR FLOATING OR FUEL OR GASOLINE OR OIL)/TI/CLMS	TI/CLMS	1.938	(A-B-C) - From the patents selected in step (B), all documents that presented in their titles and/or claims the words listed in the search terms in step (C) were excluded.

Table S2. Details of the International Patent Classification (IPC) and Cooperative Patent Classification (CPC) used in Patent Retrieving

Code	**Description**	**Classification type**
C	CHEMISTRY; METALLURGY	IPC or CPC
C02	TREATMENT OF WATER, WASTE WATER, SEWAGE, OR SLUDGE	IPC or CPC
C02F	TREATMENT OF WATER, WASTE WATER, SEWAGE, OR SLUDGE	IPC or CPC
C02F-001/32	Treatment of water, waste water, or sewage **with ultra-violet light**	IPC or CPC
C02F-001/30	Treatment of water, waste water, or sewage **by irradiation**	IPC or CPC
C02F-001/16	Treatment of water, waste water, or sewage **using waste heat from other processes**	IPC or CPC
C02F-001/14	Treatment of water, waste water, or sewage **using solar energy**	IPC or CPC
C02F-001/10	Treatment of water, waste water, or sewage **by direct contact with a particulate solid or with a fluid, as a heat transfer medium**	IPC or CPC
C02F-001/02	Treatment of water, waste water, or sewage **by heating**	IPC or CPC
C02F-009/10	Multistep treatment of water, waste water or sewage **Thermal treatment**	IPC

C02F-2201/009	Treatment of water, waste water, sewage, or sludge / Apparatus for treatment of water, waste water or sewage / **Apparatus with independent power supply, e.g. solar cells, windpower, fuel cells**	CPC
C02F-2201/32	Treatment of water, waste water, sewage, or sludge / Apparatus for treatment of water, waste water or sewage / **Details relating to UV-irradiation devices**	CPC
C02F-2201/3228	Treatment of water, waste water, sewage, or sludge / Apparatus for treatment of water, waste water or sewage / **Units having reflectors, e.g. coatings, baffles, plates, mirrors**	CPC
Y	GENERAL TAGGING OF NEW TECHNOLOGICAL DEVELOPMENTS; GENERAL TAGGING OF CROSS-SECTIONAL TECHNOLOGIES SPANNING OVER SEVERAL SECTIONS OF THE IPC; TECHNICAL SUBJECTS COVERED BY FORMER USPC CROSS-REFERENCE ART COLLECTIONS [XRACs] AND DIGESTS	CPC
Y02	TECHNOLOGIES OR APPLICATIONS FOR MITIGATION OR ADAPTATION AGAINST CLIMATE CHANGE	CPC
Y02A	TECHNOLOGIES FOR ADAPTATION TO CLIMATE CHANGE	CPC
Y02A-20/208	Technologies for adaptation to climate change / Water conservation; Efficient water supply; Efficient water use / **Off-grid powered water treatment**	CPC
Y02A-20/211	Technologies for adaptation to climate change / Water conservation; Efficient water supply; Efficient water use / **Solar-powered water purification**	CPC
Y02A-20/142	Technologies for adaptation to climate change / Water conservation; Efficient water supply; Efficient water use / **Solar thermal; Photovoltaics**	CPC
F	MECHANICAL ENGINEERING; LIGHTING; HEATING; WEAPONS; BLASTING	IPC or CPC
F24	HEATING; RANGES; VENTILATING	IPC or CPC
F24S	SOLAR HEAT COLLECTORS; SOLAR HEAT SYSTEMS	IPC or CPC
F24S-010/00	Solar heat collectors; solar heat systems / **Solar heat collectors using working fluids**	IPC or CPC
F24S-020/00	Solar heat collectors; solar heat systems / **Solar heat collectors specially adapted for particular uses or environments**	IPC or CPC
F24S-021/00	Solar heat collectors; solar heat systems / **Solar heat collectors not provided for in groups F24S 10/00-F24S 20/00**	IPC or CPC
F24S-023/00	Solar heat collectors; solar heat systems / **Arrangements for concentrating solar rays for solar heat collectors**	IPC or CPC
F24S-025/00	Solar heat collectors; solar heat systems / **Arrangement of stationary mountings or supports for solar heat collector modules**	IPC or CPC
F24S-030/00	Solar heat collectors; solar heat systems / **Arrangements for moving or orienting solar heat collector modules**	IPC or CPC

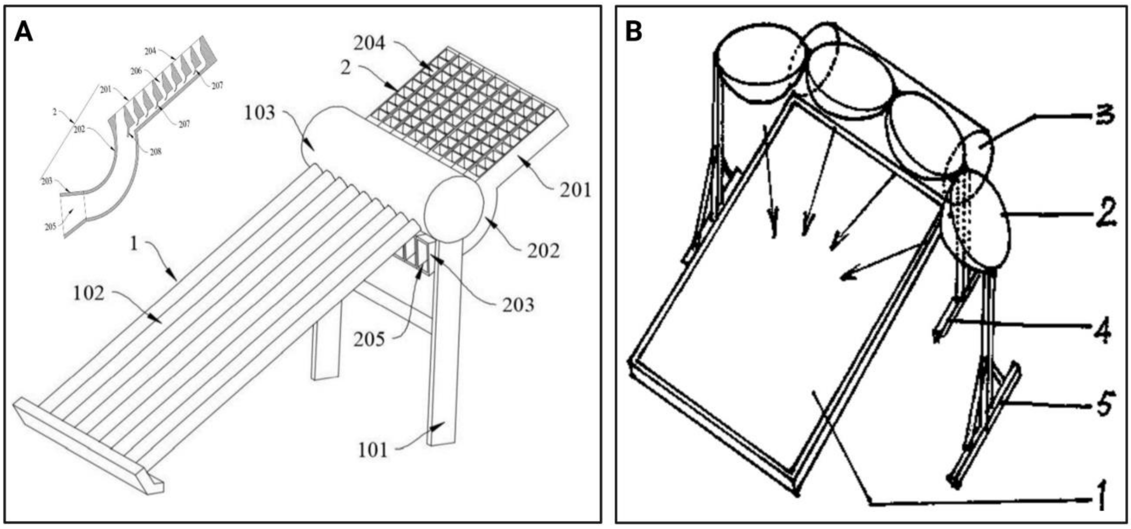

Figure S1. A – Sun light supplementation device (Xiaobing, 2021). B – Solar focus device (Huai, 2015).

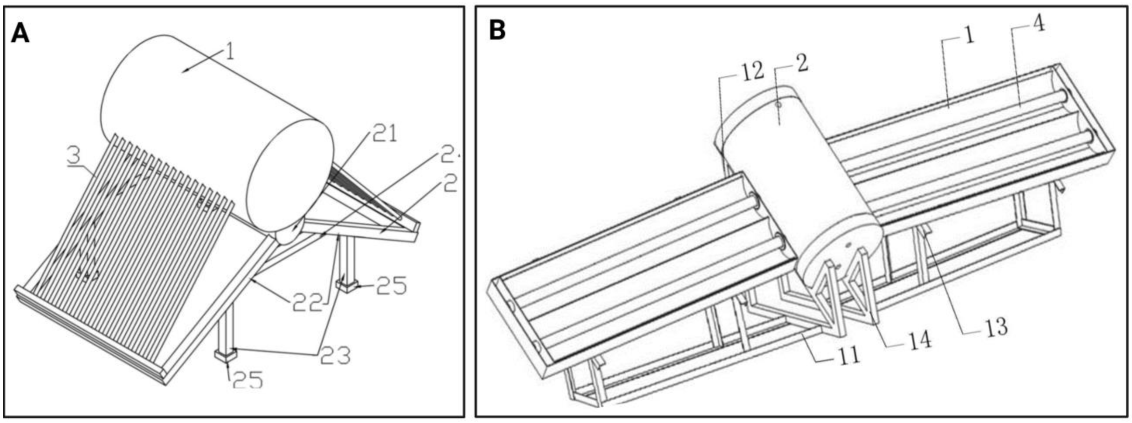

Figure S2. A – Solar water heater based on evacuated tube solar collectors arranged in an inverted V shape (Bingdong, 2018). B – Solar water heater based on evacuated tube solar collectors fixed to the focus of compound parabolic concentrators, placed inside a heat box (Shengyu and Guanghui, 2019).

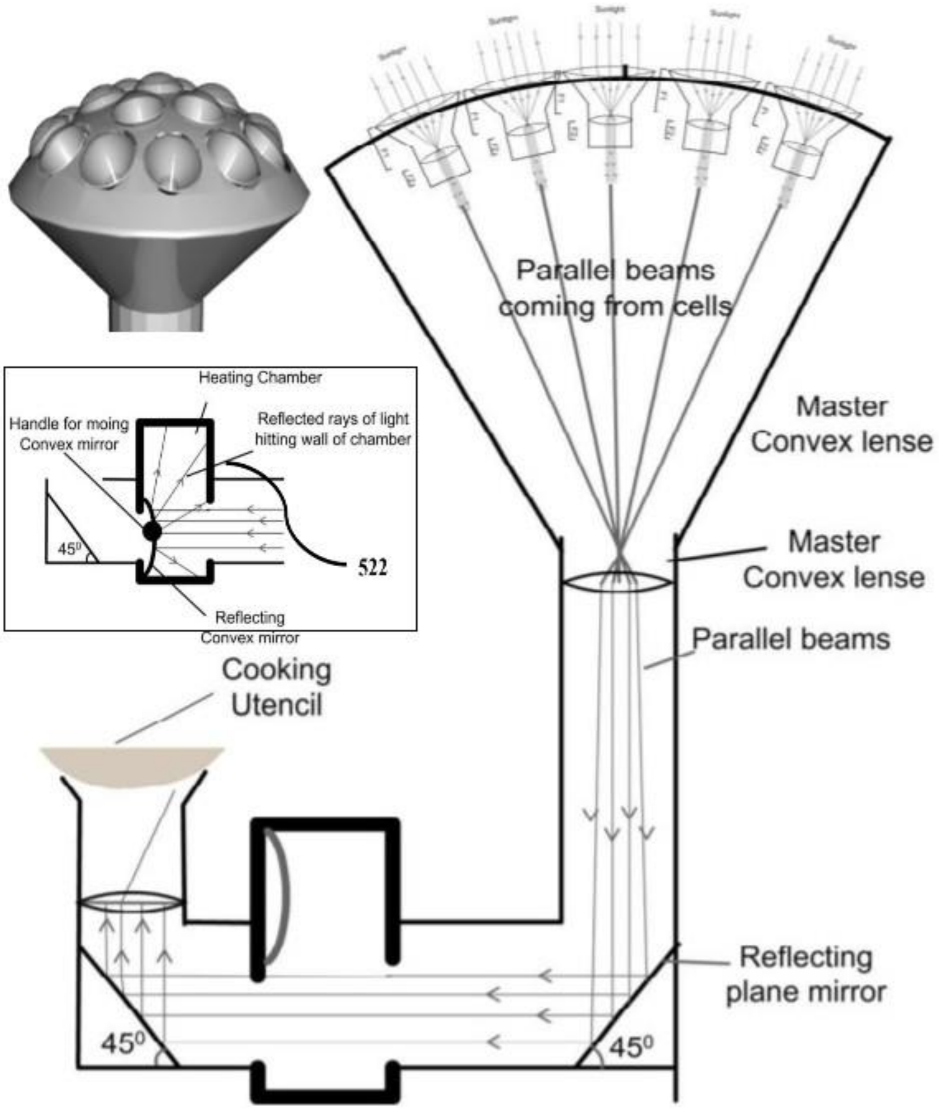

Figure S3. Indoor solar cooker (Kumar et al., 2021).

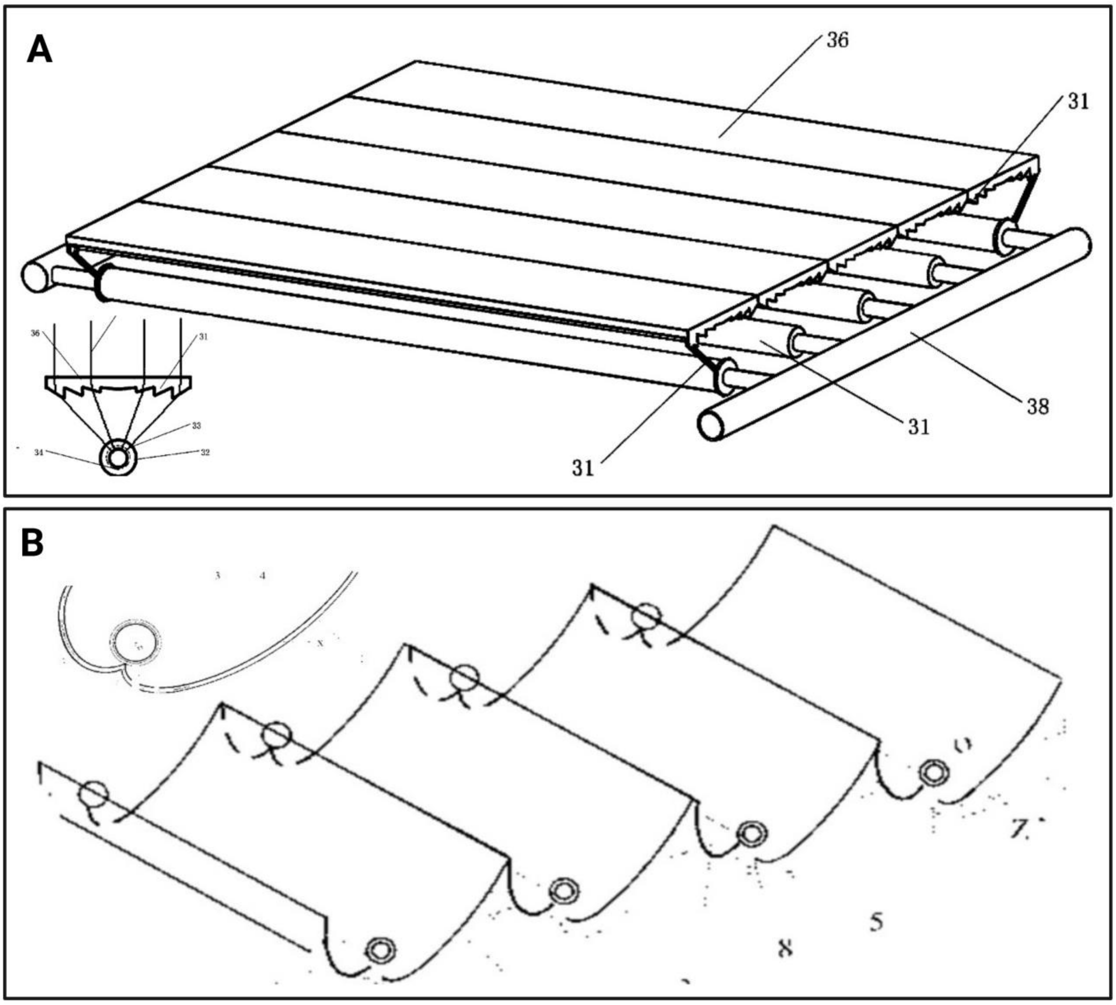

Figure S4. A – Flat plate solar collector made with concentrating fesnel lenses (Xiaodong , 2014). B – Compound parabolic concentrator enhanced by asymmetric truncation and tilt to the horizontal plane. (Yongjiu, 2012).

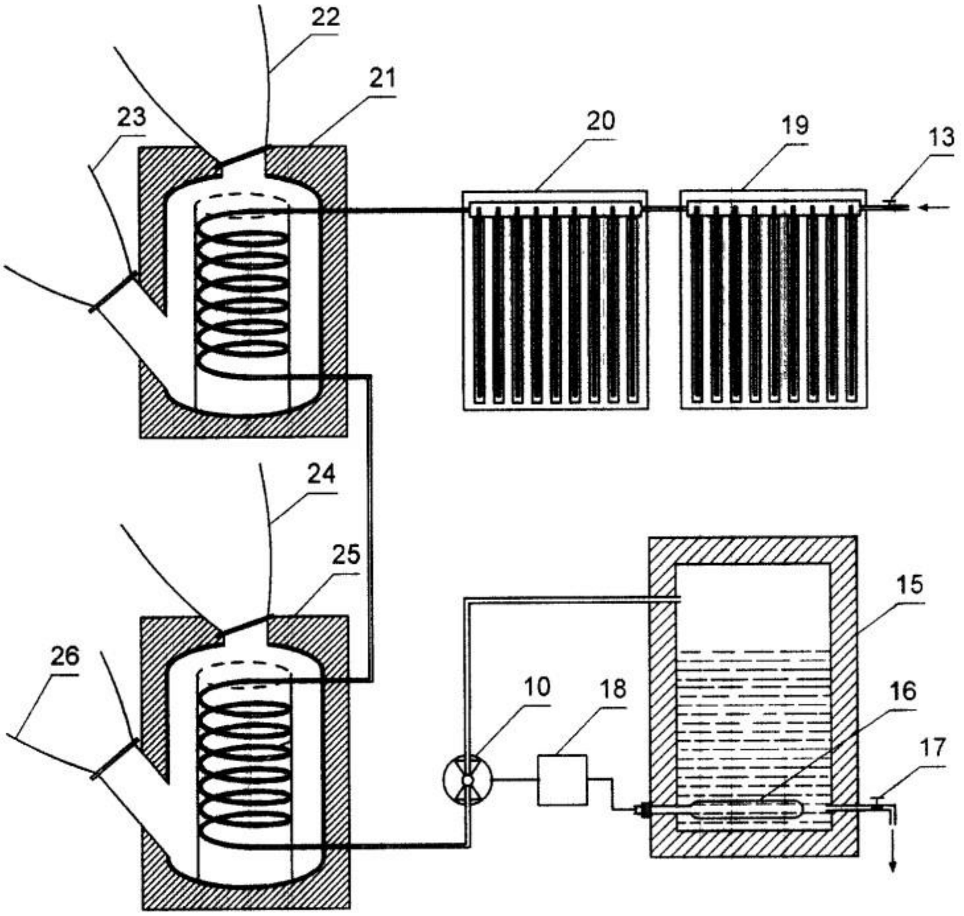

Figure S5. Thermal energy storage tank containing compound parabolic collectors fixed on its surface (Kaiyan and Hongfei, 2007).

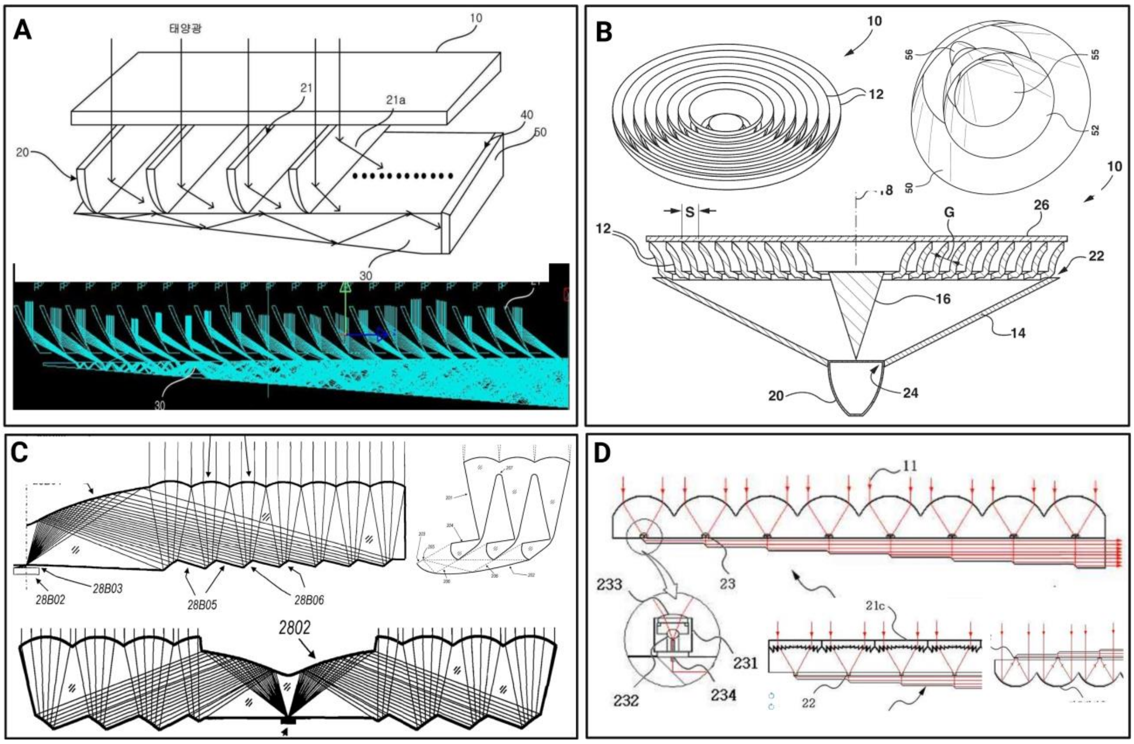

Figure S6. Solar collectors with lateral solar radiation condensing apparatus for the use of reflected light, in a linear (A (Kim and Kang, 2013), C (Carlos et al., 2009) and D (Jung, 2010)) or punctual reactor (B (James et al., 2013)).

Table S3. Pearson's correlation between variables related to water productivity in solar pasteurization systems (SOPAS).

	Initial microbial density	**Solar irradiation**	**Water temperatures**	**Daily water productivity**
Initial microbial density	1			
Solar irradiation	-0.14821	1		
Water temperatures	0.07807	-0.07643	1	
Daily water productivity	-0.55343*	0.602971*	-0.590562*	1

* - Pearson's strong correlation ($p > 0.5$).

Table S4. Pearson correlation between variables related to the productivity of drinking water in disinfection systems based on solar UV radiation (SODIS).

	Cumulative UV solar radiation	**Residence time**	**Daily water productivity**	**Log removal**
Cumulative UV solar radiation	1			
Residence time	0.605248	1		
Daily water productivity	-0.44387	-0.18284	1	
Log removal	0.96411*	0.422125	-0.51946*	1

* - Pearson's strong correlation (*p > 0.5*).

Table S5. Pearson correlation between variables related to drinking water productivity in mixed solar disinfection systems, based on heat and UV synergy (SOPAS + SODIS).

	UV fluency	**Water temperature**	**Residence time**	**Daily water productivity**	**Microbial density**
UV fluency	1				
Water temp.	0.621168567	1			
Residence time	0.653844583	-0.186804934	1		
Daily water productivity	0.135551574	0.860644249*	-0.661015*	1	
Microbial density	-0.96076892*	-0.81415234*	-0.4183425	-0.4050239	1

* - Pearson's strong correlation (*p > 0.5*).

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APÊNDICE XII

Supplementary Material

Epidemiological and Immunological Gains from Solar Water Disinfection (SODIS): A Fact or Wish?

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Article recovery strategy

The articles used in the present study were accessed through searches carried out in 6 databases, namely PubMed, LILACS, Scopus, EMBASE, ProQuest and CAPES journals, between February 28 and 29, 2022. In these databases , articles were retrieved using the following search strategy: (Impact of solar disinfection OR Solar disinfection OR SODIS inactivated OR Sunlight inactivated OR Solar inactivated) AND (Prevalence of waterborne diseases OR Prevalence of diarrhea OR Occurrence of diarrhea OR Immunity OR Immune OR Immune activation OR Immune response OR prevalence of dysentery) NO (SARS-CoV-2).

All retrieved original articles, as well as systematic review articles, reviewed by experts, written in English, with full text available, addressing the impact of SODIS use on waterborne disease prevalence were included. Articles addressing the impact of SODIS-inactivated microorganisms on immunity were also included.

Summary of results of studies that measured the impact of SODIS on the prevalence of gastrointestinal diseases

In 1996, Conroy and colleagues examined the performance of SODIS in reducing diarrhea among children and adolescents aged 5 to 16 years in Maasai settlements in Kenya's Kajiado Province. These authors found that children in the study group (who received PET bottles and instructions to perform solar water disinfection) had fewer episodes of diarrhea per week than those in the control group (4.1 vs. 4.5). Similarly, fewer episodes of severe diarrhea (sufficient to prevent them from performing their tasks) were reported in the study group than in the control group (1.7 vs. 2.3) (Conroy et al., 1996). Three years later, in another study involving 349 Maasai children under 6 years of age, these authors reported that the prevalence of severe diarrhea in the study group was lower (48.8%) compared to the control group (58.1%) (Conroy et al., 1999). A cholera outbreak that occurred sometime later in the intervention communities gave the authors an opportunity for further study. It was found that among children who drank SODIS-disinfected water, only 1.9% (3 of 155) became ill, compared with 13.9% (20 of 144) of sick children among non-SODIS users (Conroy et al. al., 2001).

The trial by Rose et al. (2006) in India involved 100 children from families instructed to use SODIS and 100 children from families without intervention who served as controls. These authors reported a statistically significant reduction in both the incidence, duration and severity of diarrhea in the intervention group, although the authors found that throughout the study 86% of the children also drank water different from that treated by SODIS. The incidence of diarrhea was 1.7 per child/year in the intervention group and 2.7 per child/year in the control group. The study further reported that the use of SODIS resulted in a 40% reduction in the risk of diarrhea.

Another study also carried out in India, in the urban slum of Sikkim, evaluated children up to 5 years old, where 65 children (52 families) were trained to use SODIS and 66 children (50 families) served as controls. After eight weeks of intervention, the prevalence of diarrhea was 7.58% among SODIS users and 31.43% among non-users; the reduction in diarrhea was 75.88% in the study group (Rai et al., 2010).

A reduction in the prevalence of diarrhea was also reported in a study by Graf et al. (2010) in the city of Yaoundé, capital of Cameroon; in this study 2,911 families were trained in the use of SODIS. The prevalence of diarrhea in children (under 5 years) was 22.8% in the intervention group compared to 31.8% in the control group. A lower prevalence (18.3%) was obtained when considering data from families that fully complied with the intervention, in these families the risk of diarrhea was reduced by 42.5%.

The study by McGuigan et al. (2011) who focused on children (under 5 years old) living in rural Cambodia, compared 426 children (375 families) using SODIS with 502 children (407 families) without intervention for one year. Adherence to SODIS during the study was greater than 90%. The mean number of days of dysentery occurrence in the intervention group was lower (0.15) compared to the control group (0.27). Children in the SODIS group had a reduced incidence of dysentery and non-dysentery diarrhea with an incidence rate ratio (IRR) of 0.50 (95% CI 0.27-0.93, $p = 0.029$) and 0.37 (95% CI 0.29-0.48, $p < 0.001$), respectively. Community use of SODIS resulted in a 50% reduction in the risk of dysentery in children.

A similar study was carried out by du Preez et al. (2011) these authors compared diarrhea incidence rates (dysentery and non-dysentery) among 555 children (404 households) using SODIS and 534 children (361 households) in the control group. A statistically significant reduction in IRR was obtained by using SODIS, for episodes of dysentery IRR = 0.55 (CI 95% 0.42 to 0.73) and episodes of non-dysentery diarrhea TIR = 0.73 (CI 95% 0 .63 to 0.84). In addition, the authors reported that anthropometric measurements (height and weight) were significantly higher in the group using SODIS. Children among SODIS users were on average 0.8 cm taller and 0.23 kg heavier.

A study by Bitew et al., (2018) in 28 rural villages in Dabat, Ethiopia, also focused on children under the age of 5. In this study, 384 children (279 households) received reactors and training to perform SODIS, and S394 children (289 households) served as controls. The incidence of diarrhea was lower in the intervention group (8.3 episodes/100 person-week observations) than in the control group (15.3 episodes/100 person-week observations). The use of SODIS resulted in a significant reduction in the incidence of diarrhea with an adjusted IRR of 0.60 (95% CI 0.52, 0.70); also resulted in a 40% reduced risk of diarrhea.

In a study conducted in Bolivia, covering 22 communities, 225 families (376 children) were trained in the use of SODIS and 200 families (349 children) served as controls (Mäusezahl et al., 2009). The study reported that the incidence rate of diarrhea in children (under 5 years) in the intervention group was 3.6 versus 4.3 episodes/year in the control group, so there was no statistically significant difference. The authors associated these findings with a lower rate of population adherence (32.1%) to SODIS.

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APÊNDICE XIII

Supplementary material

Why do low-cost point-of-use water treatment technologies succeed or fail in combating waterborne diseases in the field? Systematic review

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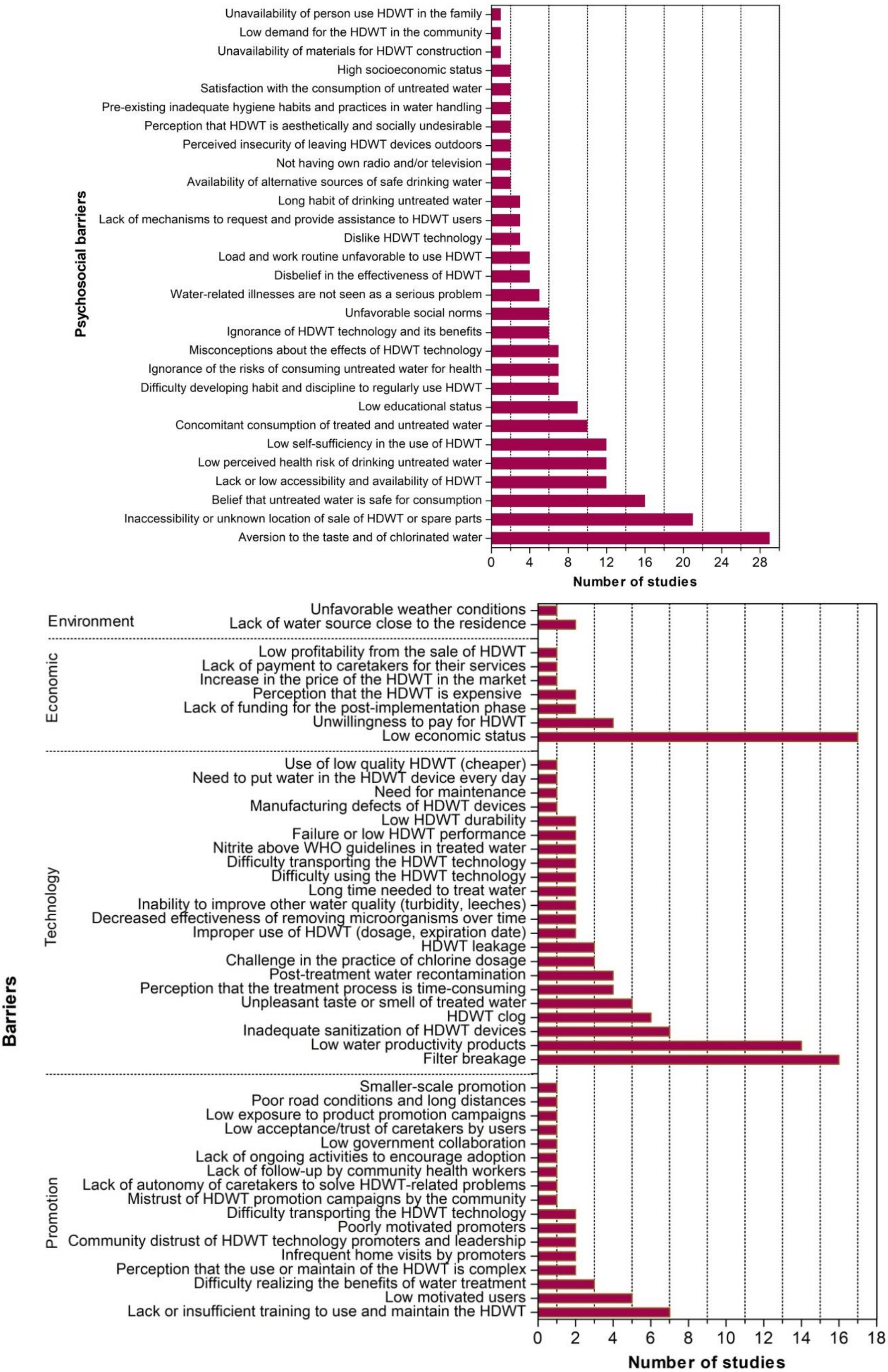

Figure S1. Number of studies identifying each of the barriers (considering all HWT's) by domain.

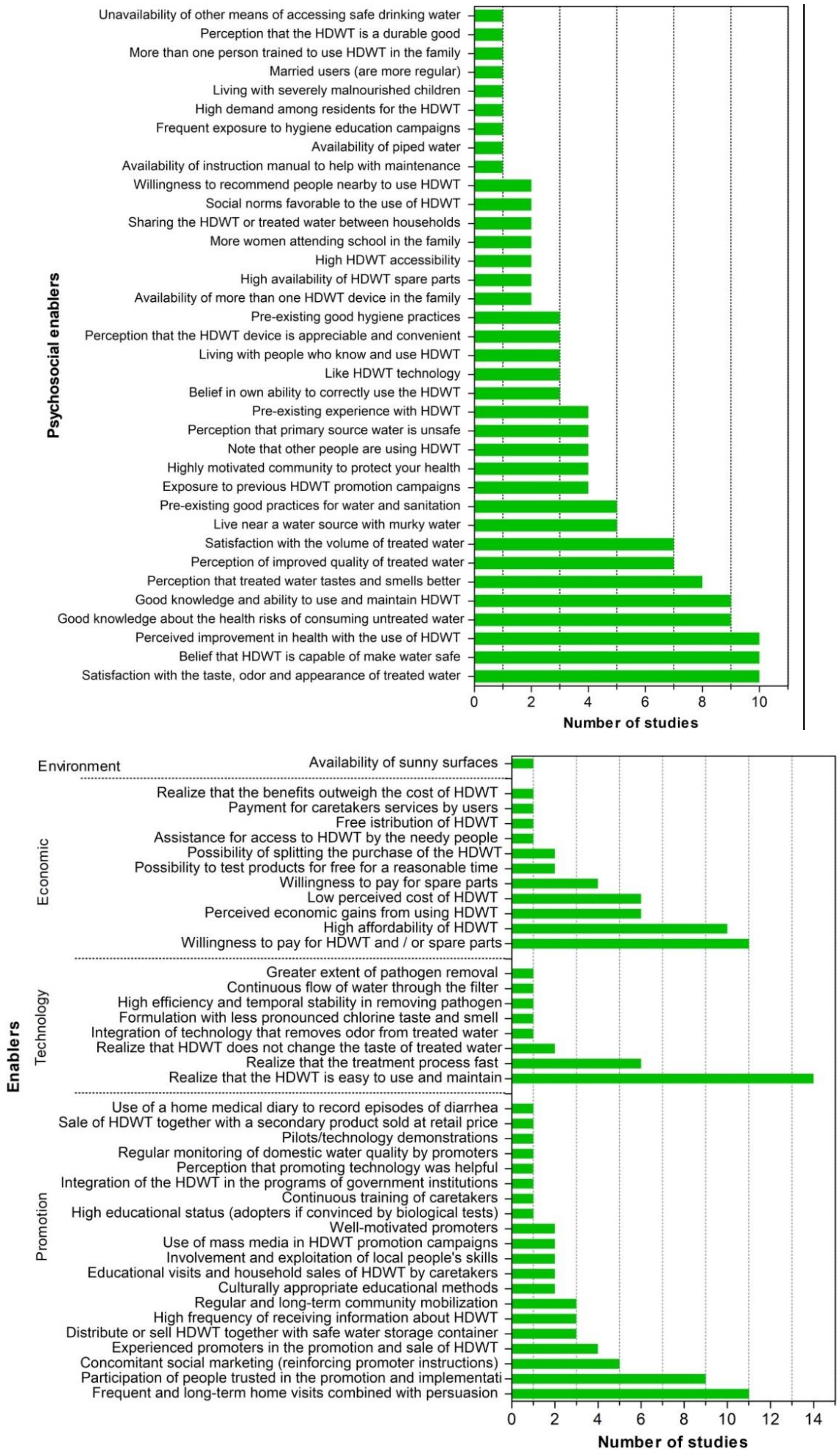

Figure S2. Number of studies identifying each of the enabler (considering all HWT's) by domain.

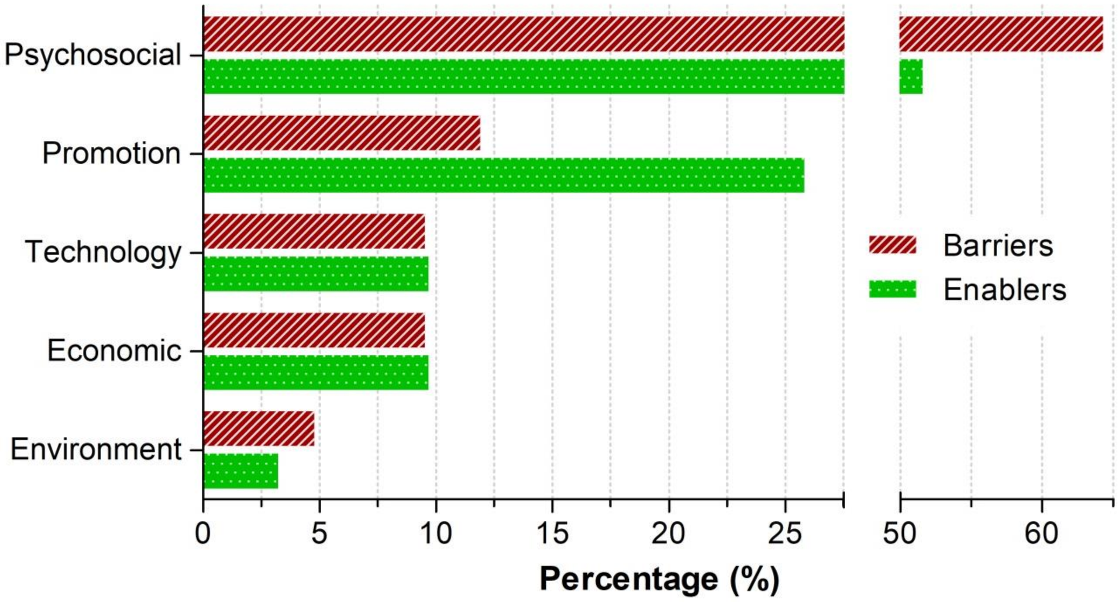

Figure S3. Distribution of barriers and facilitators of SODIS-based interventions by different domains.

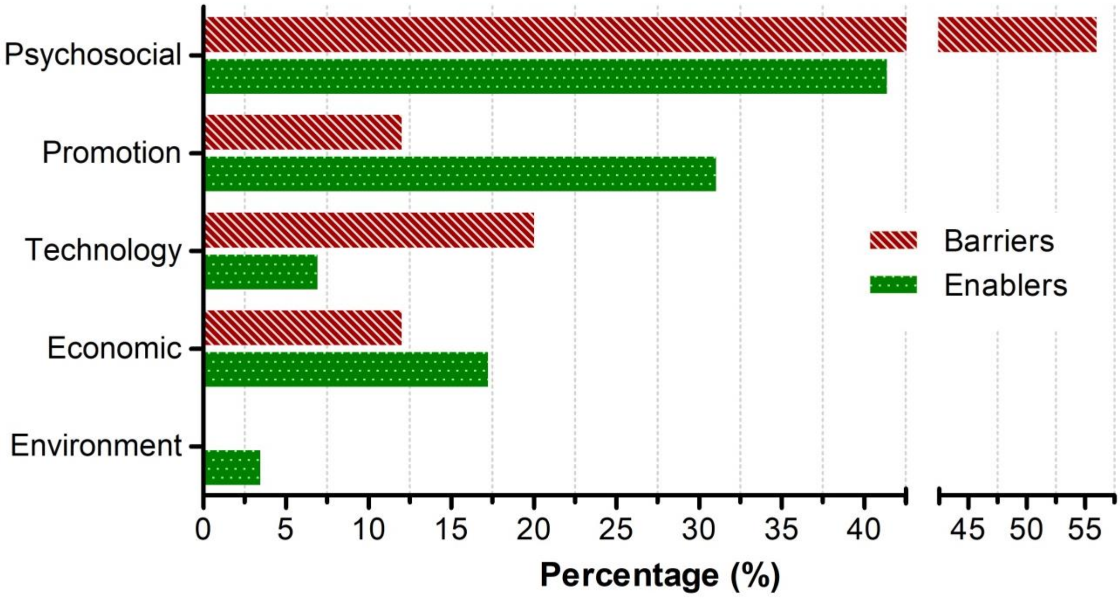

Figure S4. Distribution of barriers and enablers of chlorine-based interventions by different domains.

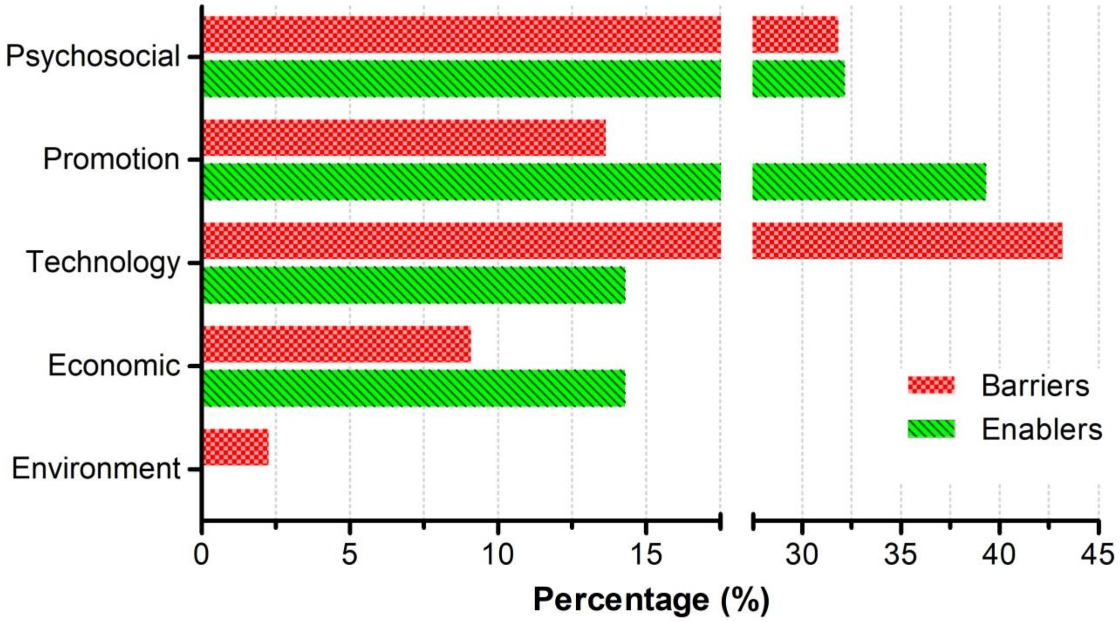

Figure S5. Distribution of barriers and enablers of interventions based on biosand filters across the different domains.

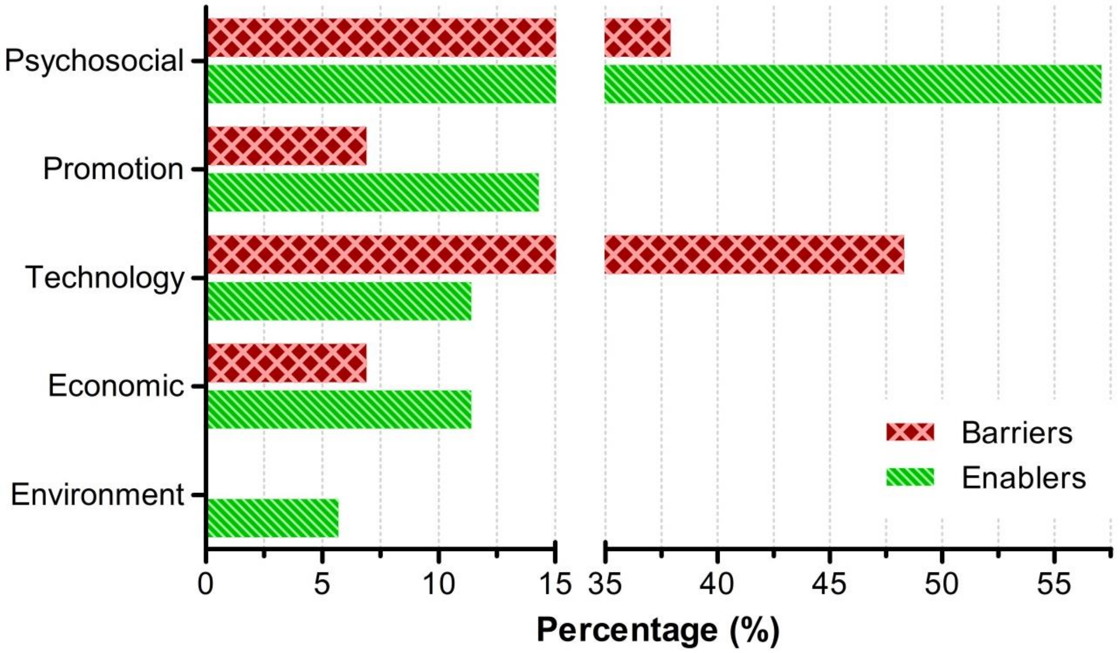

Figure S6. Distribution of barriers and enablers of interventions based on ceramic water filters across the different domains.

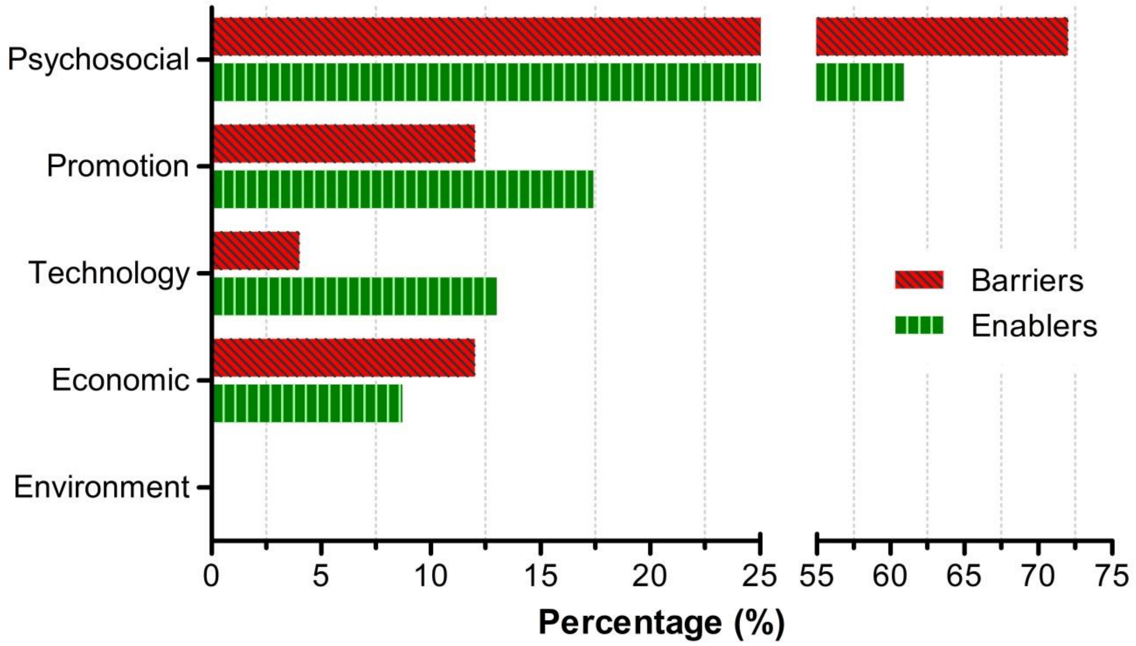

Figure S7. Distribution of barriers and enablers of interventions identified by studies that focused on HWT technologies in general.

Table S1. Barriers and enablers that interfere with each of the performance metrics of HWT-based interventions.

	Barriers	**Enablers**
Initial adoption	Availability of alternative sources of safe drinking water	Assistance (subvention) for access to HWT by the needy people
	Belief that untreated water is safe for consumption	Belief in own ability to correctly use the HWT
	Difficulty transporting the HWT technology	Belief that HWT is capable of make water safe
	Community distrust of HWT technology promoters and leadership	Concomitant social marketing (reinforcing promoter instructions)
	Difficulty using the HWT technology	Culturally appropriate educational methods
	Ignorance of the risks of consuming untreated water for health	Distribute or sell HWT together with safe water storage container
	Dislike HWT technology	Distribution of HWT
	Perception that the use and/or maintenance of the HWT is complex	Educational visits and household sales of HWT by caretakers
	High socioeconomic status	Experienced promoters in the promotion and sale of HWT
	Ignorance of HWT technology and its benefits	Exposure to previous HWT promotion campaigns
	Disbelief in the effectiveness of HWT	Frequent exposure to hygiene education campaigns
	Inaccessibility or unknown location of sale of HWT or spare parts	Good knowledge about the health risks of consuming untreated water
	Long habit of drinking untreated water	High demand among residents for the HWT
	Pre-existing inadequate hygiene habits and practices in water handling	High educational status (adopters if convinced by biological tests)

	Low economic status Low educational status Low exposure to product promotion campaigns Low government collaboration Low motivated users Low perceived health risk of drinking untreated water Misconceptions about the effects of HWT technology Mistrust of HWT promotion campaigns by the community Not having own radio and/or television Perception that HWT is aesthetically and socially undesirable Perception that the HWT is expensive Perception that the treatment process is time-consuming High educational status Poorly motivated promoters Low demand for the HWT in the community Satisfaction with the consumption of untreated water Smaller-scale promotion (induces unfavorable perception and low readiness to use SODIS) Unavailability of person use HWT in the family Unfavorable social norms Unwillingness to pay for HWT Water-related illnesses are not seen as a serious problem	High frequency of receiving information about HWT High HWT accessibility Highly motivated community to protect your health Involvement and exploitation of local people's skills Like HWT technology Live near a water source with murky water Pre-existing good hygiene practices Perception that primary source water is unsafe Perception that promoting technology was helpful Perception that the HWT device is appreciable and convenient Perception that the HWT is a durable good Perception that the treatment process fast Pilots/technology demonstrations Possibility of splitting the purchase of the HWT Possibility to test products for free for a reasonable time Pre-existing experience with HWT Participation of people trusted by communities in the promotion and implementation Pre-existing good practices for water and sanitation Use of mass media in HWT promotion campaigns Social norms favorable to the use of HWT Unavailability of other means of accessing safe drinking water Sale of HWT together with a secondary product sold at retail price Well-motivated promoters
Regular Use	Aversion to the taste and of chlorinated water Challenge in the practice of chlorine dosage Concomitant consumption of treated and untreated water Difficulty realizing the benefits of water treatment Difficulty developing habit and discipline to regularly use HWT Infrequent home visits by promoters Lack of ongoing activities to encourage consistent adoption of the intervention Lack of water source close to the residence Load and work routine unfavorable to use HWT Long time needed to treat water Low acceptance/trust of caretakers by users Low motivated users Need to put water in the HWT device every day Perceived insecurity of leaving HWT devices outdoors Unfavorable weather conditions	Availability of piped water Availability of sunny surfaces Perception of improved quality of treated water Formulation with less pronounced chlorine taste and smell Frequent and long-term home visits combined with persuasion Highly motivated community to protect your health Integration of technology that removes odor from treated water Involvement and exploitation of local people's skills Live near a water source with murky water Living with people who know and use HWT Living with severely malnourished children Married users (are more regular) More than one person trained to use HWT in the family More women attending school in the family Note that other people are using HWT Perceived improvement in health with the use of HWT Continuous flow of water through the filter (reminder for routine use) Perception that primary source water is unsafe Perception that the HWT is easy to use and maintain Perception that treated water tastes and smells better Pre-existing good practices for water and sanitation

		Regular and long-term community mobilization Regular monitoring of domestic water quality by promoters Satisfaction with the taste, odor and appearance of treated water Satisfaction with the volume of treated water Sharing the HWT or treated water between households Use of a home medical diary to record episodes of diarrhea
Sustained use	Decreased effectiveness of removing microorganisms over time Concomitant consumption of treated and untreated water Difficulty transporting the HWT technology Failure or low HWT performance Filter breakage HWT clog HWT leakage Lack of autonomy of caretakers to solve all HWT-related problems Inability to improve other water quality (turbidity, leeches) Inaccessibility of materials for building HWT Inadequate sanitization of HWT devices Increase in the price of the HWT in the market Infrequent home visits by promoters Improper use of HWT (dosage, expiration date) Lack of follow-up by community health workers Lack of funding for the post-implementation phase Lack of mechanisms to request and provide assistance to HWT users Lack of ongoing activities to encourage consistent adoption of the intervention Lack of payment to caretakers for their services Lack or insufficient training to use and maintain the HWT Lack or low accessibility and availability of HWT Low acceptance/trust of caretakers by users Low HWT durability Low profitability from the sale of HWT Low self-sufficiency in the use of HWT Low water productivity products Manufacturing defects of HWT devices Need for maintenance Nitrite above WHO guidelines in treated water Poor road conditions and long distances Post-treatment water recontamination Unpleasant taste or smell of treated water Use of low quality HWT (cheaper)	Availability of instruction manual to help with maintenance Availability of more than one HWT device in the family Continuous training of caretakers Good knowledge and ability to use and maintain HWT Greater extent of pathogen removal High affordability of HWT High availability of HWT spare parts High efficiency and temporal stability in removing pathogen (≥3log for > 2 years) Integration of the HWT in the programs of government institutions Low perceived cost of HWT Payment for caretakers services by users Perceived economic gains from using HWT Perceived improvement in health with the use of HWT Perception that the benefits outweigh the cost of HWT Pilots/technology demonstrations Pre-existing good hygiene practices Regular monitoring of domestic water quality by promoters Use of a home medical diary to record episodes of diarrhea Willingness to recommend people nearby to use HWT Willingness to pay for HWT and / or spare parts (at a sustainable price)